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The motor room from roughing mill end. The first three main drives are for the horizontal edger and roughing stands R1 and R2. The twin flywheels on the horizontal edger and R1 are mounted on each side of the gear-box, and the liquid starter and automatic slip regulator associated with these two drives can be seen adjacent to their respective machines

Electrical Drives for the New Brinsworth 16-inch Hot Strip Mill of Steel Peech & Tozer

By M. H. JAHN, B.Sc.(Eng.), Grad. I.E.E., Metal Industries Division.

THE NEW BRINSWORTH 16-inch Hot Strip Mill, installed to meet the growing demands of modern industry for high quality narrow width steel strip, embodies in its design the most up-to-date features in electrical, mechanical and civil engineering. The output from this mill will be used mainly for the manufacture of tubes, pressings for the motor-car industry, and further cold rolling.

Until this new mill commenced production the requirements for narrow width steel strip, i.e., up to 9 inches wide, were met within the United Steel Companies Limited by single strip mills, commissioned in the early 'twenties. With the increase in production of this group of companies, the existing mills were being operated at full capacity and the necessity for expansion and replacement became progressively more apparent.

Accordingly, in 1954, plans were initiated for a new project known as the 'Brinsworth Mill', to cover the installation of a hot strip mill, shearing and trimming lines, tandem and temper mills.

Fig. 1.—General view of the hot strip mill looking towards the finishing train and coilers. Roughing stand No. 2 is in the left foreground

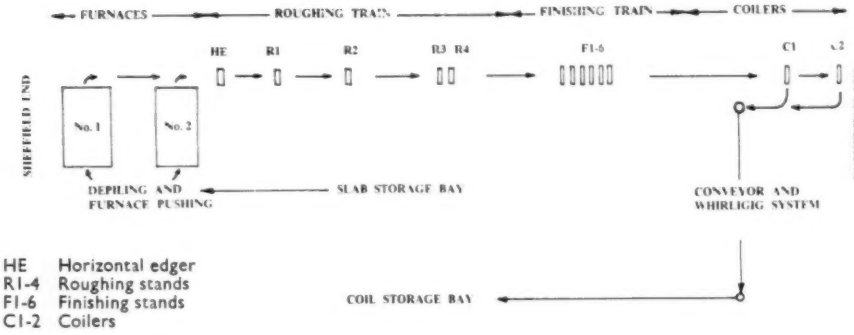


Fig. 2. — Basic flow diagram of mill

HE Horizontal edger
R1-4 Roughing stands
F1-6 Finishing stands
C1-2 Coilers

Orders for the first section, the hot strip mill, were placed in 1955 and the mill commenced production two years later, in the summer of 1957.

The Brinsworth site is situated on the main road from Sheffield to Rotherham, opposite the existing Templeborough Works of Steel Peech & Tozer. Civil construction of the plant was carried out with Mr. Donovan H. Lee acting as civil consultant. The mill itself, excluding the reheating furnaces supplied by Stein and Atkinson Ltd, was designed and installed by the Loewy Engineering Company. The English Electric Company was the main contractor for almost the whole of the electrical equipment driving the mill.

Before describing in detail the mill drives and associated electrical equipment, a general description of the mill and its operation is desirable.

The Mill

The mill (Fig. 1) is designed for an annual output of 250,000 tons of hot rolled coiled strip based on sixteen-shift operation per week. The majority of this product is mild steel (0·08 to 0·13% carbon), but special steels having carbon content up to 0·85% are also rolled.

The reheated slabs, produced originally on the cogging and slabbing mills in the Templeborough Works, have a nominal length of 28 feet, a thickness

TABLE I

MILL DRIVE DATA

Stand (See Fig. 2)	Drive Motor			Gear Ratio	Roll Data		
	h.p.	r.p.m.	Type		Dia. in.	r.p.m.	f.p.m.
HE	350	500	A.C. slipring	12·72/1	16–20½	39·3	200*
R1	700	500	A.C. slipring	9·17/1	21	54·5	300
R2	1,200	428	A.C. synchronous	9·17/1	21	46·7	257
R3	1,200	428	A.C. synchronous	9·17/1	21	46·7	257
R4	1,200	425–850	D.C. shunt wound	7·89/1	21	53·9–107·8	296–592
F1	1,200	425–850	D.C. shunt wound	5·47/1	14	77·5–156	285–572
F2	1,750	357–760	D.C. shunt wound	3·00/1	14	119–253	437–930
F3	1,750	357–760	D.C. shunt wound	1·95/1	14	183–390	672–1,434
F4	1,750	357–760	D.C. shunt wound	1·34/1	14	266–566	974–2,070
F5	1,750	357–760	D.C. shunt wound	1/1	14	357–760	1,314–2,793
F6	1,200	425–925	D.C. shunt wound	1/1	14	425–925	1,569–3,390

* Due to difference in roll groove sizes this figure is only indicative.

of 3 inches and a width dictated by the end product. A small quantity of half-length slabs is also used. From the furnaces the slab is carried by roller tables through the mill train. The basic flow diagram in Fig. 2 illustrates the sequence of rolling operations.

In order to give the flexibility of operation required, each stand of the mill is individually driven by its own electric motor. The motors are of varying types to suit the requirements of the particular drive ; Table I gives the basic data of the machines and mill. These machines and the majority of the electrical control equipment are installed in a motor room alongside the mill (see frontispiece).

The mill is fed from two 60 tons per hour furnaces. These are of the push-through type and are equipped with depiling arrangements, weighing machines and transfer tables. The furnace is heated by oil fired burners situated at the end of the tonnage zone and of the soaking zones. Slabs are pushed through on skids and are heated to a temperature of 1,250°C.

After the furnaces the first mill stand is the horizontal edger which acts as a scale breaker ; the slab having been turned on edge before entry into the rolls, the scale drops away from the surface leaving clean metal for entry into the remainder of the mill. The next four stands complete the roughing train and consist of two open stands R1 and R2 following by two close-coupled stands R3 and R4.

From R4 the slab is fed to the delay tables where it is held until the correct rolling temperature has been reached for entry into the six-stand continuous finishing train. This temperature is of the order of 1,050°C.

Following the last stand of the finishing train, a motorised run-out table carries the strip to the two mandrel coilers situated at the Rotherham end of the mill bay. The coilers are equipped with automatic handling gear which transfers the completed coils on to the conveyor system, and this in turn delivers them into the coil storage bay.

A rotating flying shear is installed just prior to the finishing train, which can be used for cropping the nose end to present a clean entry to the first stand of the finishing mill. Edging control is provided by three sets of vertical edging rolls positioned in front of stands R3 and F1 and after F2.

In passing through the mill the initial slab is

TABLE II

TYPICAL REDUCTION SCHEDULE FOR MILL

Stand (See Fig. 2)	Roll diameter, inches	Width inches	Reduction %	Thickness out inches	Length feet	Rolling speed f.p.m.
—	—	11	—	3	28·0	—
HE	—	10	—	3	30·85	—
R1	21	10	26·6	2·2	42·0	300
R2	21	10	34·5	1·44	64·3	300
R3	21	10	38·2	0·89	103·8	300
R4	21	10	34·8	0·58	159·5	460
F1	14	10	42·2	0·335	276	315
F2	14	10	44·8	0·185	500	571
F3	14	10	36·7	0·117	790	905
F4	14	10	30·8	0·081	1,154	1,301
F5	14	10	27·1	0·059	1,585	1,790
F6	14	10	18·7	0·048	1,925	2,200

Fig. 3. — Close-coupled mill stands R3 and R4 driven respectively by an a.c. 1,200 h.p. synchronous motor and a d.c. 1,200 h.p. variable-speed motor

reduced to a continuous strip which may be up to one-third of a mile long and down to 0·042 inch thick. The reduction taken in each stand is based on designed reduction schedules of which a typical example for producing 0·048 inch material is reproduced in Table II.

Main Drives—Roughing and Finishing

The roughing train, as its name implies, takes the first few heavy reduction passes, and this results in the first stands being on load for short high-peak periods. Economically, the most satisfactory method of driving such stands is to use a slipring induction motor in conjunction with a flywheel which absorbs energy from the motor during light load periods and supplies it to the mill during rolling. As shown in the frontispiece, this has been adopted in the case of the horizontal edger and roughing stand R1. The necessary motor speed droop on load, permitting the flywheel to give up

Fig. 4.—Six-stand continuous finishing mill with one of the vertical edgers in left foreground. Part of the vertical edger between stands 2 and 3 can be seen. 10 h.p. d.c. screwdown motors with magnetic brake and clutch are mounted on top of the mill stand with their operating controls in the cabinets mounted on the side

its energy, is obtained by means of a fixed slip resistor on the horizontal edger and an automatic slip regulator on Stand R1 where the longer passes require a more uniform control in comparison with the horizontal edger.

Roughing stands 2 and 3 are each driven by a salient pole synchronous motor designed for working peaks of 2·5 times full load torque to meet the heavy rolling duty requirements. The two machines are reactor-started and are each fitted with automatic unity power-factor control, preventing heavy lagging reactive kVA demands being made on the supply during rolling.

The second of these drives is close-coupled by the strip to stand R4 and is shown in Fig. 3. Stand R3, being synchronous-motor driven, is a 'hard' drive having no speed droop with load. Therefore, control must be available on stand R4 to allow for the change in draftings of the mill, and this stand is accordingly driven by a 1,200 h.p d.c. motor with variable speed setting control and individually fed from a 1,000 kW 600 volt grid-controlled rectifier bank.

Fig. 5.—Rotherham end of motor room with six finishing stand motors. Nos. 5 and 6 are set closer to the wall as no gear-box is required. Shear M.G. set and constant-voltage exciter sets in foreground. Screwdown contactor panel on right and remaining M.G. and exciter sets at far end of room

The stock, having passed through the roughing train, is held by the shear operator on the delay tables until it has cooled to the correct rolling temperature and is then allowed to enter the finishing mill. This is a six-stand continuous mill, shown in Fig. 4, capable of delivery speeds up to 3,300 feet per minute. Each stand is individually driven by a 600 volt d.c. variable-speed motor, the last two being direct driven as shown in Fig. 5. The d.c. supply for the motors is from two 3,500 kW rectifier banks equipped with grid control for starting and voltage holding purposes.

Two edgers are included in the finishing mill train, one in front of the first stand, which can be seen in Fig. 4, and a second mounted after Stand 2. To ensure that speed differences between the edgers and the main drives do not either damage the strip or overload the edger drives, the control is arranged for the edger motors to have a 20% regulation characteristic throughout the speed range.

Control and Operation—Roughing and Finishing Train

As applicable throughout the mill, all control of main drives, and a large percentage of the auxiliaries, is carried out from raised pulpits overlooking the mill. The final arrangement of pulpits and desk layouts was reached after consultation between the mill designer, the production and electrical staffs of Steel Peech and Tozer, and The English Electric Company. The prime consideration was to provide control stations in which the operators would be comfortable, quiet and with an unrestricted view of the mill.

Fig. 6.—Pulpit controls for roughing mill operator. Headboard contains all instrumentation and permissive switching signalling lights. Roll diameter adjustment rheostats for correcting f.p.m. readings are also on headboard. Desks contain all switching units, the selector switches at the rear and operative switches at the front

All pulpit controls have accordingly been designed for seated operators, the pulpits are sound-proofed and are provided with air conditioning plant, and to ensure unrestricted viewing, ' mock-ups ' of some of the pulpits were made before the designs were finalised. Figs. 6 and 7 show typical arrangements of these pulpits, for the roughing mill and finishing mill respectively.

For the roughing train there are two such pulpits, one controlling the horizontal edger with its associated auxiliaries and the second controlling the remainder of the roughing train. For the main drives the pulpit operators are provided only with ' permissive ' switches, the actual starting of the motors being initiated by the motor room attendant. This method was considered advisable as, with the preponderance of a.c. drives drawing heavy starting currents from the supply, suitable staggering of the starting peaks can be ensured.

In the roughing train, Stand R4 is the only one requiring speed setting control by the pulpit operator, since the remaining stands are a.c. driven. Speed setting is effected by a motorised shunt field rheostat controlled from a pulpit of similar type to that shown in Fig. 7 for the finishing mill.

For the finishing mill, however, all control of the main drives is given to the pulpit operators. The two rectifier equipments are first energised by the motor room attendant ; the d.c. system is then energised from the pulpit.

Each rectifier bank supplies three motors and is designed to operate at any voltage from 360 to

Fig. 7.—Finishing mill pulpit, showing operator positions 2 and 3

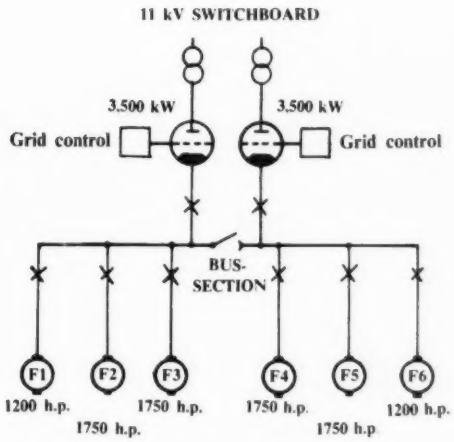


Fig. 8.—Main circuit connections of finishing mill

600 volts. Fig. 8 shows the main circuit connections. Before starting the mill the operators close the individual stand circuit-breakers ; the closing of the main rectifier breakers then initiates acceleration of the mill. A phase shifter provides the control for the rectifiers up to the operating voltage, magnetic amplifiers being used to maintain the voltage at the pre-set value.

The split busbar arrangement allows the two sections to operate at different voltage levels, permitting a widening of the speed cone to meet special rolling requirements. If necessary, the bus-section switch can be closed and the two rectifier equipments run in parallel.

Once the mill has accelerated to normal speed, individual adjustment of the speed of each stand is available from coarse and vernier rheostats in the shunt field circuits. The coarse rheostats are of the motorised ' English Electric ' roller track type, mounted in the basement. Fig. 9 shows the rheostats for stands 5 and 6. With a fast high-production mill of this type it is essential that stand speeds are held accurately to the values set by the operators, and for this purpose automatic speed holding control is provided on each stand to maintain the speed to within $\frac{1}{4}\%$ of the pre-set value.

Additional automatic control is included to assist the operators in obtaining and maintaining the correct speed relationship between stands. This consists of a loop-lifter position signal which adjusts the motor speeds to maintain the interstand loop, and hence the stand speed relation, at correct pre-determined levels.

With the voltage variation of 360 to 600 volts required from the rectifiers, poor power factors would result from the use of grid control to obtain the lower voltage levels. Accordingly, on-load tap-changers are provided on the rectifier transformers. These are automatically set to give a tap position most suitable to the operating voltage required.

Master and supervisory control of the main drives for both the roughing and finishing mill is carried out from open-type boards with all components mounted on polished slate panels. Fig. 10 shows the finishing mill control board.

Associated with the control boards are the 400 cycle magnetic amplifiers. These are chassis mounted units fitted into cubicles with full monitoring of referencing and output windings. The

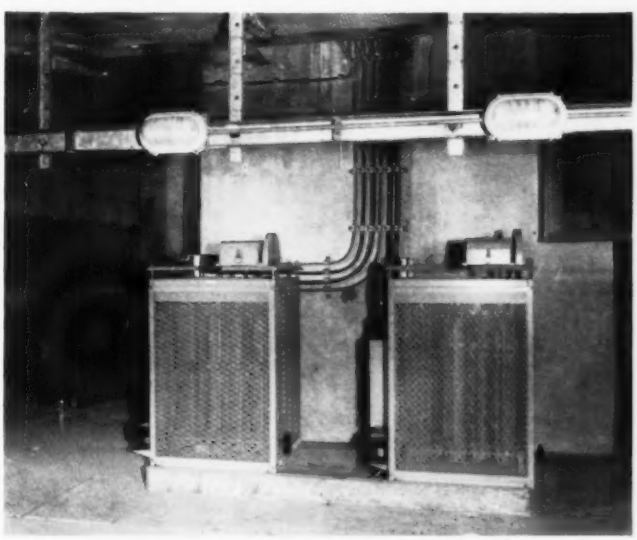


Fig. 9.—' English Electric ' roller track type field rheostats for finishing stands 5 and 6. To the left are the two axial flow booster fans for these two stands

roughing train magnetic amplifier board shown in Fig. 11 is a typical example.

Fig. 11.—*Roughing train magnetic amplifier board. Bias and referencing adjusting resistors are mounted on a panel behind the doors at the top of the cubicles*

Flying Shear

The drive for the flying shear, just prior to the finishing train, is controlled from a separate pulpit above the mill floor. The shear is of the 'stop-start' type in which the blades are normally held in a rest position just clear of the stock. On initiating 'cut' the blades accelerate to cutting speed in one revolution, cut, and decelerate to stop before meeting the strip again. A limit switch automatically returns the blades to the rest position.

The high acceleration and deceleration rates required for a shear of this type need extremely accurate and fast-response control systems. To meet this requirement acceleration and deceleration takes place under current limit, controlled by 400 cycle magnetic amplifiers housed in a separate cubicle adjacent to the open-type shear control panel and similar to the equipments used on the main drives.

'Cut' on the shear is always initiated manually, as the shear is primarily intended for cropping the nose or tail end. Provision is made, however, for continuous cutting to produce sheets from stock held on the delay table if the finishing mill is unable to accept the slab for rolling. As far as possible the actual cutting speed is matched to the speed of the stock by taking a speed reference from the finishing train or the tables, depending on the

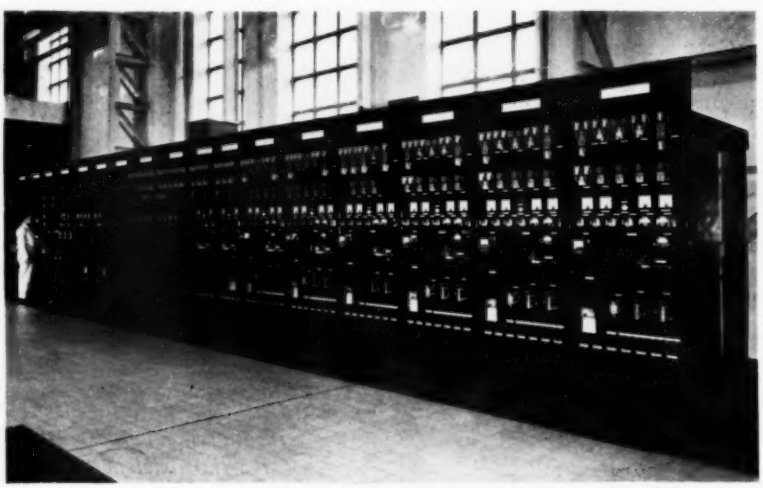


Fig. 10.—*Finishing mill control board. Stand controls at right, rectifier and referencing control at left*

Fig. 12.—Flying shear driven by 'English Electric' CMR1619 motor. To left of motor is local shear-testing control station. Beyond the shear is the finishing mill and its pulpit which is partly hidden by the shear unit

cutting requirements. The speed reference used is selected by the operator prior to initiating cutting.

The arrangement of the shear and motor is shown in Fig. 12, the motor being an 'English Electric' mill-type 'CMR' machine. It is interesting to note that this machine is one of the first motors manufactured in the A.I.S.E. 600 range above the 618 size.

Auxiliary Drives

Handling of the stock during the complete sequence, from slabs entering the furnace to strip leaving the finishing mill, is carried out by electrically driven auxiliaries. In addition, certain basic auxiliaries, such as mill lubrication, rely on electrical plant for their correct operation.

The English Electric Company was responsible

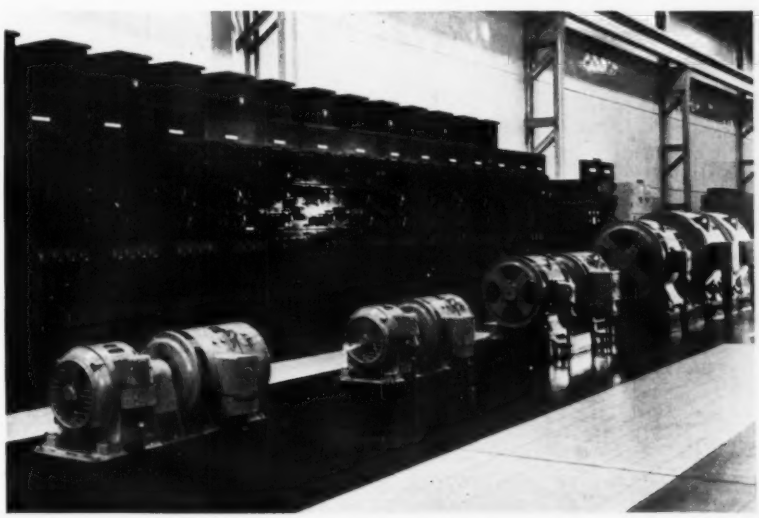


Fig. 13.—Contactor board (supplied by Igranic Electric Company) for d.c. constant-voltage screw-downs on finishing mill. In foreground are constant-voltage exciter sets with flying shear M.G. set in line. Partly hidden by M.G. set are control and 'Magamp' boards for flying shear

Fig. 14.—*Contactor board 'C' (supplied by G.W.B. Furnaces Ltd) for a.c. constant-voltage auxiliaries on finishing mill*

for engineering the control schemes and providing the equipment to the requirements of the mill maker and owners, and ensured that the individual drives were co-ordinated to give an integrated scheme with the pulpit and desk controls, control board arrangements and general distribution system. Control gear for these auxiliaries was supplied by the Igranic Electric Company and Gibbons & Wild-Barfield Electric Furnaces Ltd, as sub-contractors to The English Electric Company. Two of the contactor panels are shown in Figs. 13 and 14.

The auxiliaries associated with the furnace depiling and pusher systems are all driven by 230 volt d.c. constant-voltage motors with reversing inductive time limit control. Slabs are placed by the crane on to depiling skids, and the depiler pusher then transfers the slabs on to a weighing machine where the weight is automatically recorded. The slabs are then further pushed on to the depiler lifting table. Fig. 15 shows the depiling system, situated between the two furnaces. From the depiler lifting table, slabs are transferred individually to either of the two furnaces. Pushing the

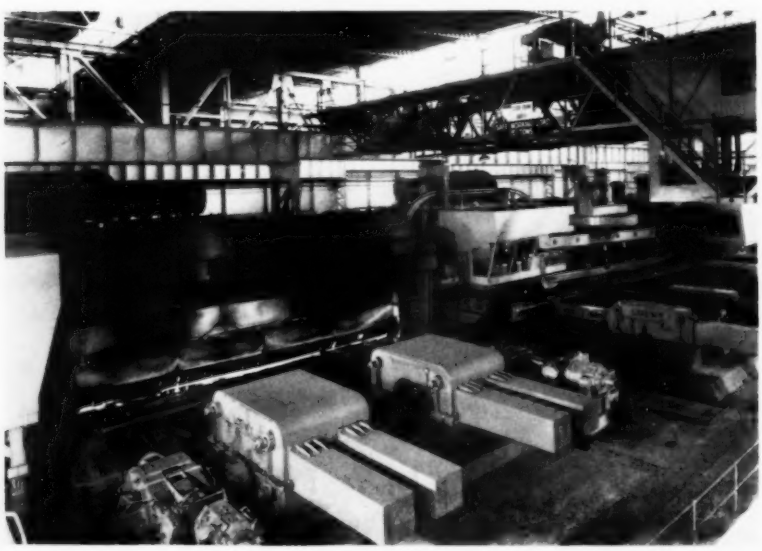


Fig. 15.—*Ingoing side of furnaces, showing slabs on special crane lifting tackle ready to be placed on depiler. In foreground is No.* 1 *furnace pusher driven by two d.c. motors, one on each side of pusher. Operating pulpits for depiling and controls for each furnace can be seen*

slab into the entry side of the furnaces causes a slab to be ejected from the delivery side on to the furnace discharge tables. Co-ordination of furnace selection and furnace pushing is arranged by a signalling system between the operative pulpits.

Roller tables are used for carrying the slab through the mill train between the main mill stands. The tables directly associated with the furnaces and horizontal edger, where accurate positioning control is required, are powered by d.c. mill-type motors. The remainder of the tables have direct driven rollers powered by a.c. low speed induction motors.

Manipulation of the slab in front of and behind the horizontal edger is controlled from the horizontal edger pulpit. Manipulators turn the slab on edge for entry into the rolls and return it to the flat position after the pass has been taken. Each manipulator has two separate motions, each motion being powered by a d.c. variable-speed mill-type motor. In order to provide the operator with the maximum flexibility in controlling these drives, ' joystick ' controllers were installed. These have two sets of contacts, one set operated by forward/back movement and the other by sideways movement. If required, both movements can take place simultaneously.

Screwdowns on all the roughing stands are driven by a.c. motors, one motor being used per stand. The screwdown setting indication is by dials visible from floor-mounted control pedestals from which the adjustment is made. Adjustment of individual screws for roll levelling is made manually. For the finishing mill, much faster and more accurate setting of the screws is required than could be obtained with a.c. motors. Each stand is therefore equipped with two d.c. screwdown motors, allowing independent setting of each screw. For normal roll adjustment, both motors operate together and are held in step by a magnetic clutch. Position indication of both screw settings is given on Cirscale type Selsyn position indicators.

As already described, two vertical edgers are provided in the finishing mill train for width control of the strip. In addition an edging stand is included in the mill train in front of Stand R3. This is driven by a 150 h.p. mill-type motor supplied from the d.c. 230 volt shop supply. Normal series resistance starting is employed with shunt field control for speed setting.

In addition to the descaling of the slab by the horizontal edger, a number of high pressure water descaling sprays operating at 1,500 lb per sq in are mounted on the mill. These, coupled with the efficient scale breaking on the horizontal edger, produce an extremely clean high-grade end product. The descaling sprays are controlled by solenoid valves in the supply pipelines. These valves can be operated either manually by the pulpit operators or automatically by infra-red photo-cell units situated above the mill train, which detect the position of the slab.

Lubrication of the mill stands and gear-boxes is an important consideration in a mill of this type, and systems are installed giving immediate warning of failure and initiating mill shutdown where necessary.

The roughing mill stands are equipped with fabric bearings using water as a lubricating medium. On/off control is provided by solenoid valves automatically controlled by the main drive circuits. Automatic injection of ' Ensis ' protective fluid is arranged at shutdown of the mill stands. Roller bearings are used throughout the finishing train, and here a straight flood-lubricated system is provided with main and standby oil pumps.

The main gear-box lubrication on each mill train is provided by an oil pressure system. To ensure continuity of supply and consistency of pressure, four pumps are used, one acting as standby. The standby pump is automatically brought into use on failure of oil pressure, and appropriate alarms are given. Due to the high viscosity of the lubricating oil under cold conditions, provision is made for the inclusion of thermostatically controlled oil heaters.

Loop lifters are provided between each pair of finishing-mill stands to support the strip between the stands and thereby control looping and so avoid a ' cobble '. The loop lifter consists of a balanced arm pivoted at one end and driven by an a.c. torque motor through gearing ; raising or lowering can be effected by operator-controlled foot pedals or automatically by load relays. Under automatic control, position-sensing circuits can be

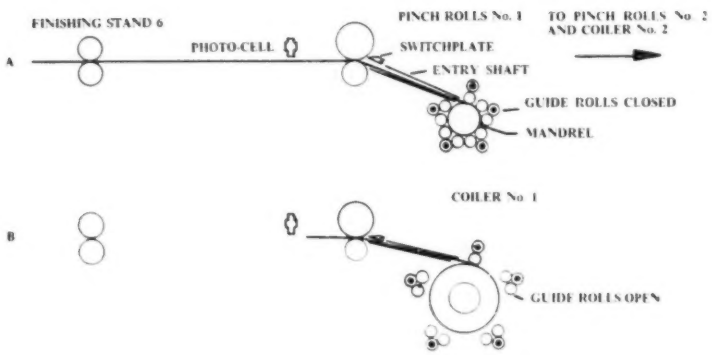


Fig. 16.—Diagrammatic arrangement of coiler equipment

made operative which correct the mill stand speeds to maintain the loop at a pre-determined height. This prevents excessive looping or interstand tension.

To ensure entry of the strip into the coilers at the correct temperature, cooling water sprays are mounted above the run-out table. These produce lamina-flow water and are controlled by the mill floor operative.

In addition to the foregoing auxiliaries there are units such as roll balance pumps, grease systems and hydraulic pumps, all of which are equally essential to maintain output on the mill.

Coilers

As the strip leaves the finishing mill it is carried by run-out tables to the two hot strip mandrel coilers. These coil the hot strip under controlled tension, and are among the first to be installed in Great Britain. The method of obtaining tension control is very similar to that used on modern cold mills, and much of The English Electric Company's wide experience in the cold-mill field was used to develop a successful scheme for this equipment.

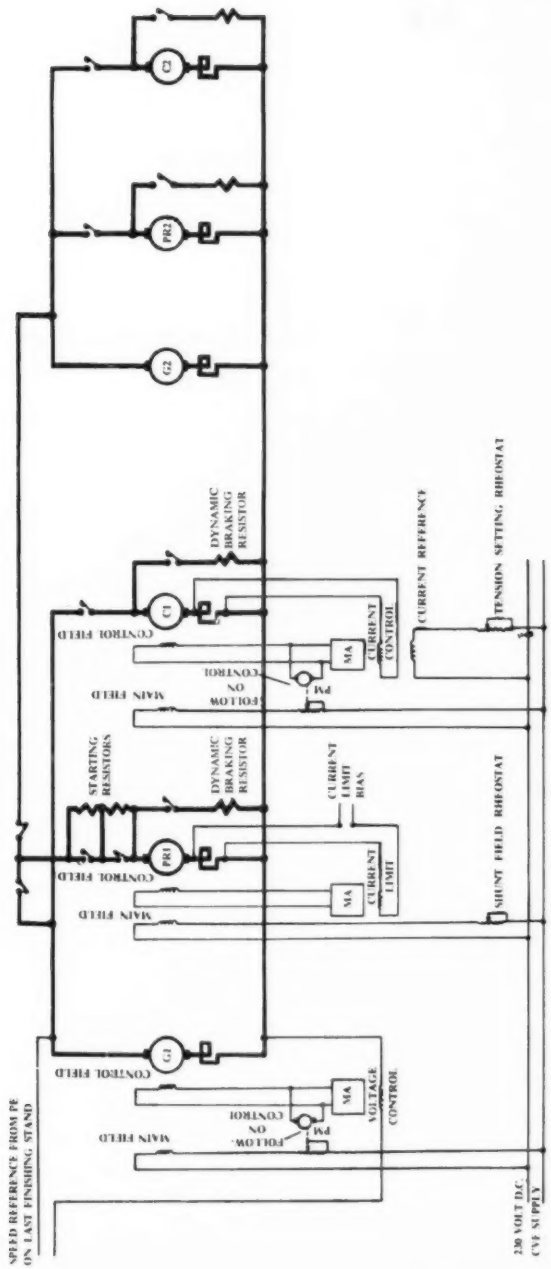
However, a basic difference from the cold-mill technique is that the strip enters the coilers at its outgoing speed from the finishing mill, which can be as high as 3,300 ft per min, and the coiler equipment must be designed to accept the strip at these high speeds and to feed it round the mandrel in such a manner that the coil is formed and tension is developed back to the finishing mill.

As the nose of the strip is carried along the run-out tables it enters the pinch rolls. These are of different diameters as shown in Fig. 16 and operate to deflect the nose end through the entry shaft to the mandrel, which is already rotating at the correct speed to receive the strip. Surrounding the mandrel are clusters of powered guide rolls which direct the nose end round the collapsed mandrel to form the first turn of the coil. Once the first turn is completed the mandrel is expanded, causing tension to be developed ; the guide rolls can then be removed and coiling continues with tension between the mandrel and last finishing stand.

When the tail end leaves the finishing stand, tension is maintained by regeneration of the pinch roll motor. As the tail end enters the coiler, the top guide roll is closed as shown in Fig. 16(B) to control the tail end as the coiler comes to rest.

The control of the pinch roll and coiler motors has two basic requirements ; one is to have the equipment running at the correct speed to receive the strip, and the second is to maintain the tension during coiling. The basic circuits to meet these requirements are shown in Fig. 17.

To ensure that the pinch roll and mandrel motors are running at the correct speed, their armature voltage is maintained at a value proportional to the outgoing speed from the finishing mill and their shunt fields are pre-set. The Ward-Leonard generator supplying the two motors is excited from a pilot exciter driven by the last finishing stand, and a magnetic amplifier servo-loop ensures that



G Generator
PR Pinch roll
C Coiler
MA Magnetic amplifier
PE Pilot exciter
PM Pilot motor
CVE Constant-voltage exciter

Note : Controls for G2, PR2 and C2 as for G1, PR1 ane C1

Fig. 17.—Basic schematic diagram of coilers

Fig. 18.—Coiler pulpit, showing special desks designed to house the large number of setting-up controls and emergency manual initiation 'Consol' switches. There is one desk per coiler with a control master selection desk between the two operators

changes in the finishing mill speed are rapidly and accurately reflected by equivalent changes in the generator voltage.

With this correct speed relationship the strip tension is proportional to the coiler-motor armature current. The tension control detects changes in this current resulting from build-up of the coil, and operates to maintain the current at a constant value by strengthening the motor field as the coil diameter increases.

Current limit controls are also included in the pinch roll circuits to give a low value of back tension when the strip is in the finishing train and coiler, so ensuring that the tension is taken back to the finishing mill. As the tail end leaves the finishing mill the current limit is removed to allow full tension to be developed by regeneration on the pinch roll motor. As the No. 1 pinch roll has to run whichever coiler is being used, changeover circuits are provided to connect its motor to the operative Ward-Leonard loop.

From the foregoing it will be seen that a large number of sequence operations are involved requiring split-second timing. Repetitive accuracy of initiation of these sequences could not be maintained manually, and full automation of all coiler operations and the change-over which alternates the two coilers is therefore provided. Automatic initiation of sequences is obtained from a load relay on the finishing

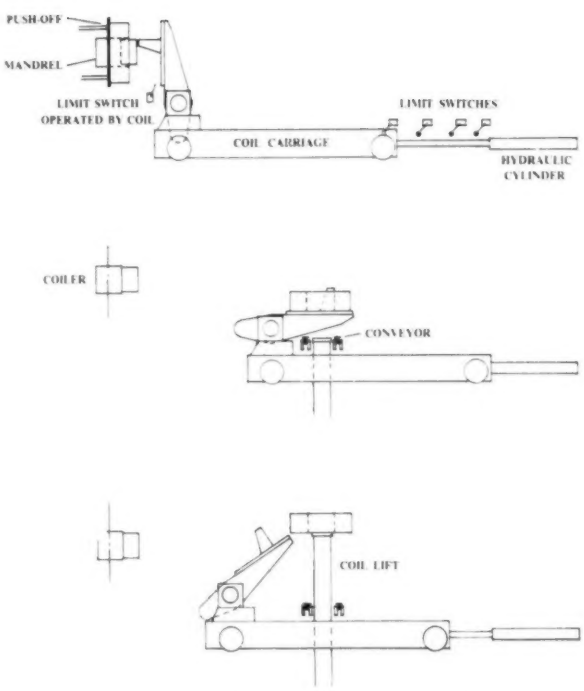


Fig. 19.—Diagrammatic arrangement of push-off and coil carriage

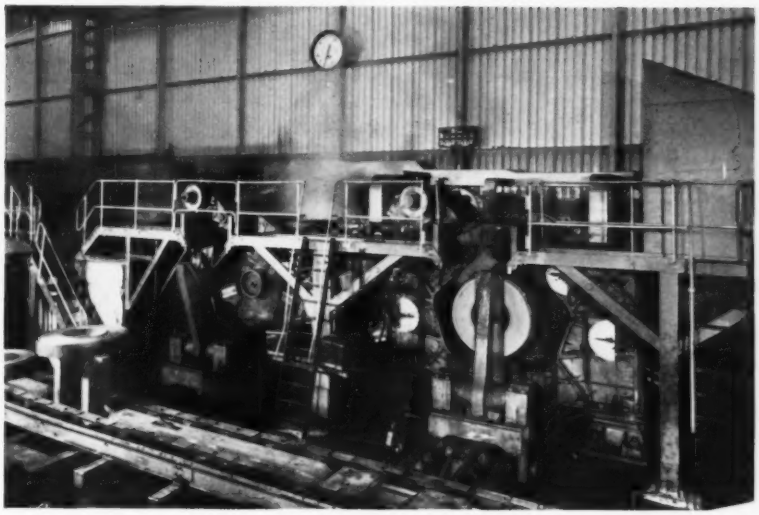


Fig. 20.—General view of coilers. On left a coil from Coiler 1 is just being lowered on to conveyor while mandrel and guide rolls are already ready to receive a further coil. Coiler 2 has just finished coiling, with coil pushed on to coil carriage

mill and a photo-cell situated prior to the coilers ; these detect the nose and tail of the strip and operate in conjunction with process timers and memory circuits.

Full trimming adjustment of all timers, motor fields and tension setting is readily available to the operators in the pulpits overlooking the two coilers. In addition, manual control of all circuits is provided for maintenance and emergency operation. Since similar automatic and manual controls are included for the coil handling and conveyors, a serious problem arose in designing a desk with all the controls within reach of the operator. This was overcome by the desk arrangement shown in Fig. 18, utilising special ' Consol ' switches developed for such applications.

Coil Handling

When the coil has been completed and the coiler brought to rest the automatic coiling sequence is finished. The operator then inches the coil round to position the tail end correctly and initiates the automatic coil handling controls.

For each coiler there is a push-off and coil carriage which transfers the completed coil from the mandrel to the conveyor serving both coilers. The arrangement of these items is shown diagrammatically in Fig. 19. The coil is pushed from the

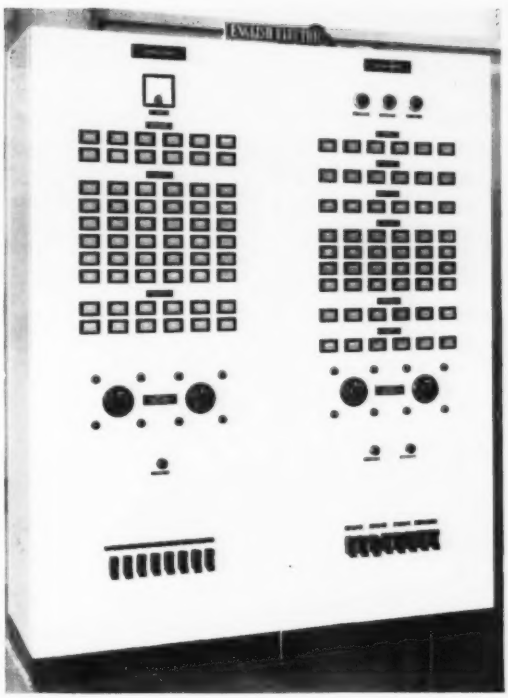


Fig. 21.—Alarms panel showing fault alarm windows. Test switches for maintenance checking of alarm circuits are shown below windows

mandrel on to the raised portion of the coil carriage which is then lowered to bring the coil into a horizontal position, and the complete carriage unit moves to position the coil above the conveyor. Raising the coil by the coil lift allows the carriage to be returned to the coiler, and the coil is then lowered on to the conveyor. Limit switches are used extensively to obtain the necessary sequencing and interlocking.

Fig. 20 gives a general view of the two coilers with the handling mechanisms in various stages of operation. The coiler conveyor feeds the coils to a whirligig which turns them through 90°, placing them on the delivery conveyor on which they pass to the coil storage bay. Here a further whirligig transfers the coils on to the unloading conveyor system. From initiation of push-off to arrival at the unloading station all the sequences are automatically controlled and initiated.

It has been found in practice that the installation of what may appear to be over-complicated automatic sequencing of coilers and coil handling is amply justified by the elimination of operators' errors in controlling the equipment. In fact, it is difficult to visualise two operators attempting to manage manually the complete equipment with a maximum production rate of the order of one coil every forty seconds.

Alarms and Shutdowns

With a modern high-production mill such as this new strip mill, involving increasing quantities and complexities of control and circuits, it becomes difficult for maintenance personnel readily to trace and correct faults. At the same time, the cost to production of even the smallest fault which causes a stoppage of the mill reaches disturbing proportions.

The English Electric Company accordingly installed a comprehensive alarm system to give immediate indication and warning of any fault and of its seriousness. This system is centralised on an alarms panel situated in the motor room and shown in Fig. 21. On the occurrence of a fault the relevant

TABLE III

MILL PULPIT SHUTDOWN WARNINGS

Control position affected	Type of Shutdown	Warnings to other Pulpits				
		No. 5 Finishing Mill	No. 4 Shear	No. 3 Roughing Mill	No. 2 Horizontal Edger	No. 1 Furnaces
No. 6 pulpit Coilers	Electrical instantaneous and manual stop feeding warning.	Stop feeding	Emergency cut	None	None	Stop feeding
No. 5 pulpit Finishing mill	Electrical instantaneous and manual stop feeding.	—	Emergency cut	None	None	Stop feeding
	Electrical 200 second time delay.	—	None	None	None	Stop feeding
	Electrical 90 second time delay.	—	Stop feeding	None	None	Stop feeding
No. 4 pulpit Flying shear	Electrical fault	—	—	None—rely entirely on loud hailer and intercommunication system		
No. 3 pulpit Roughing mill	Electrical instantaneous and manual stop feeding.	—	—	—	Stop feeding	Stop feeding
	Electrical 90 second time delay.	—	—	—	None	Stop feeding
No. 2 pulpit Horizontal edger	Electrical instantaneous	—	—	—	—	Stop feeding
	Manual stop feeding	—	—	—	—	Stop feeding

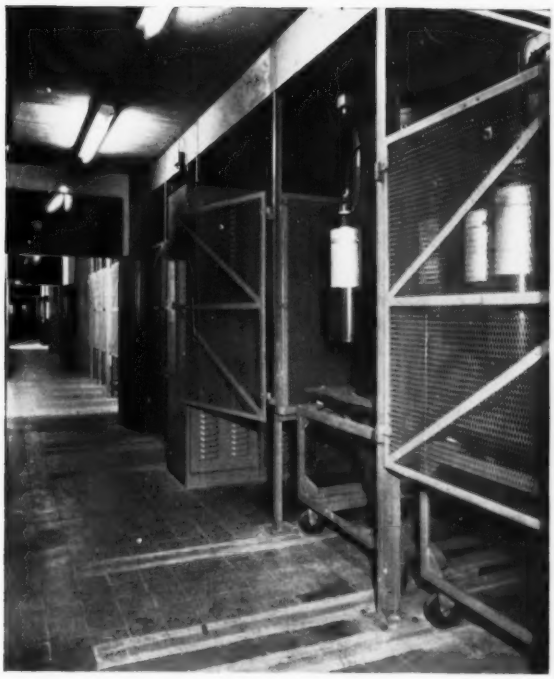


Fig. 22.—Rear view of rectifier enclosure showing trolley-mounted rectifier tanks. The dividing doors, shown open, are closed during operation to separate the automatic ventilation system for the various rectifier equipments. Temperature control thermostats can be seen above the tanks

window is lit and audible alarms are sounded. Immediate action can then be taken by the maintenance personnel to correct the fault, which has already been ' pin-pointed '.

More serious faults requiring immediate or time-delayed shutdown of the mill also give visual and audible alarm warnings in all the pulpits, so that operators can take immediate action to prevent unnecessary 'cobbles' and resultant loss of production. Provision is also included for the pulpit alarms to be initiated by pulpit operatives to give warning of mill hold-ups.

Operation of the pulpit alarm system has been based on three points at which stock can be most easily removed. These are the reject slab gear for rejecting slabs before they enter the horizontal edger, the flying shear for cutting up stock after it leaves the roughing train, and a cobble bundler for clearing cobbled strip out of the finishing train. The alarms tell the

Fig. 23.—Separate rectifier enclosure formed from 'English Electric' Unitised sheet steel cubicles and blanking pieces. In foreground are first two finishing stand motors, and on right is common control section of finishing train contactor panel

furnace operatives not to push any further slabs, and give a signal to one of the three selected stations to stop any stock at that position for ultimate removal. Table III gives the effects of alarm initiation from any of the pulpits, and shows how the foregoing principle is put into operation.

Rectifier Installation

Mention has already been made of the grid controlled rectifier equipment for the finishing mill main drives and roughing stand 4 equipment. In addition there are 1,000 kW of 230 volt distribution rectifiers. The total installed rectifier plant is therefore nine megawatts and comprises twenty-four ' English Electric ' Type PVS1341 sealed steel tank rectifiers grouped according to the size and duties of the various drives.

For such a large installation a greater multiplicity of phases is needed than can be obtained economically on any one individual equipment, and special phase-shift windings were added to the transformers to balance individual six phase and twelve phase equipments and so give a large proportion of overall forty-eight-phase operation on the supply.

To allow maximum accessibility for maintenance of the equipment, the rectifier tanks are mounted on trolleys as shown in Fig. 22. They are installed behind shallow cubicles which house all the associated equipment such as anode fuses and ignition gear. The cubicles are formed from ' English Electric ' Unitised sheet steel units and are combined with additional blanking pieces to form the rectifier enclosure within the motor room, as seen in Fig. 23.

Temperature control of the rectifier equipments is extremely important in mills of this type, to enable the plant, at any time, to meet the peak rolling loads of the mill. For this purpose a ventilation system is installed within the rectifier enclosure, automatically controlled by thermostats mounted in the air stream which operate the dampers and heaters. Under cold conditions air is recirculated within the enclosure as shown as Condition A in Fig. 24. Additional heat is supplied if necessary by the space-heaters. As the temperature rises on load, additional cooling air is taken

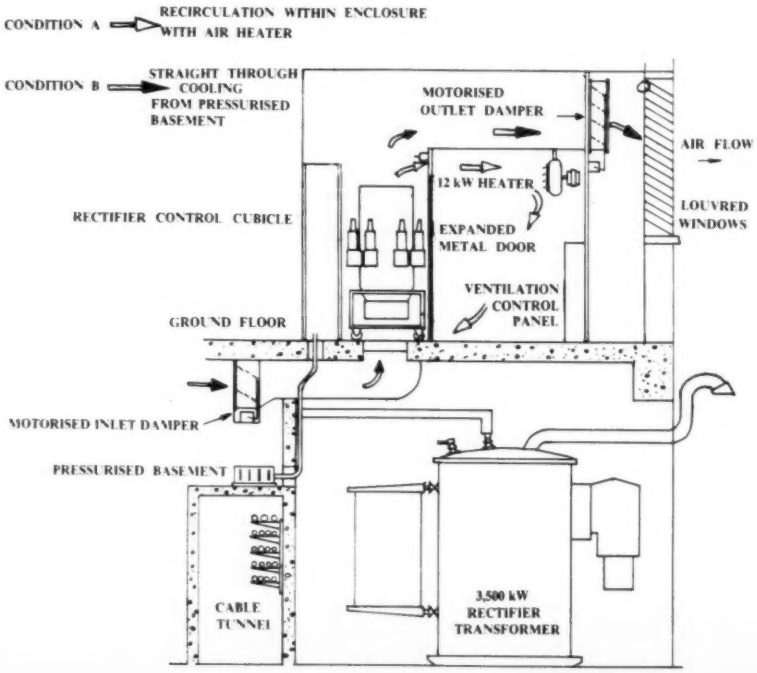
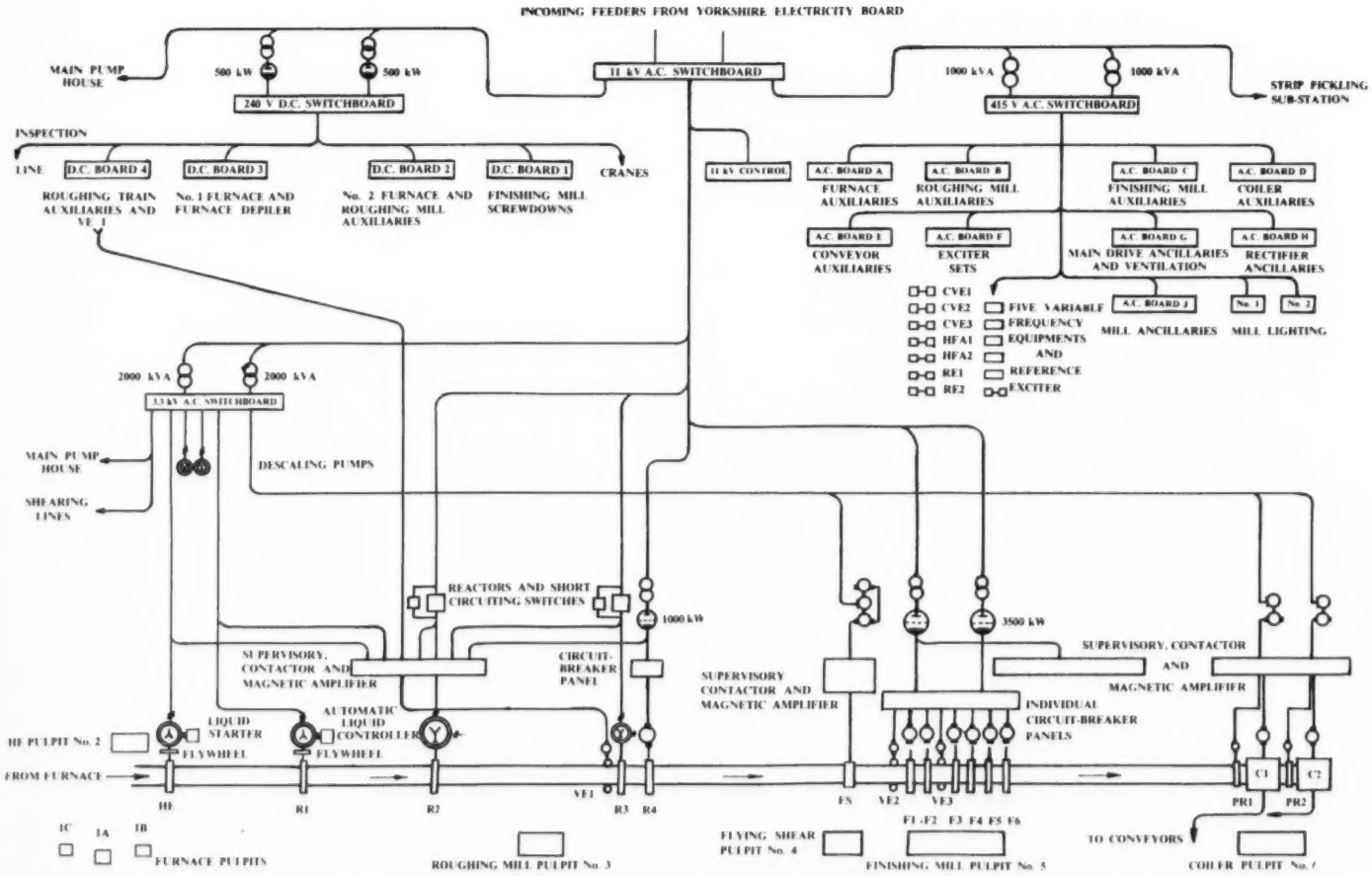


Fig. 24. — Cross-sectional diagram of rectifier enclosure, showing ventilation arrangements



HE	Horizontal edger	PR	Pinch roll
R	Roughing stand	C	Coiler
VE	Vertical edger	CVE	Constant-voltage exciter
FS	Flying shear	HFA	High-frequency alternator
F	Finishing stand	RE	Reference exciter

Fig. 25.—Line diagram of electrical equipment

from the pressurised basement and exhausted to atmosphere, shown as Condition B.

Ventilation

Apart from the rectifiers, whose ventilation system has already been described, a total loss up-draft system is installed for supplying the necessary cooling air to the main drive machines.

Outside air is drawn through filters by main input fans situated at the Sheffield end of the motor room. These pressurise the basement at a low pressure of the order of one inch w.g. From the basement, individual axial flow booster fans are used to supply air to each of the d.c. variable-speed mill motors of which two are shown in Fig. 23. In the case of the roughing stands, all of which have constant-speed drives, the motors are naturally ventilated. Cool air is however made available from the basement via the motor pits.

Power Supply and Distribution

In the preceding sections of this article the various aspects of the mill have been described together with the electrical requirements to drive the mill. All the electrical equipment is supplied by a distribution system originating from 11 kV incoming feeders whose voltage is stepped down by transformers to give supplies at 3·3 kV and 415 volts. The 230 volt d.c. services are fed from constant-voltage rectifiers.

The arrangement of the main circuit-breaker boards and the split-up of the numerous constant-voltage contactor boards are shown in Fig. 25 which gives a line diagram of the electrical equipment.

Special 230 volt constant-voltage supplies for control and reference circuits, and 400 cycle 400 volt supplies for the magnetic amplifiers, are obtained from exciter sets fed from the 415 volt system.

Conclusion

Since the commencement of rolling in the summer of 1957 the new Brinsworth Mill has been giving operational control and tonnage throughput well up to the requirements for which the equipment was designed. As a result of operational experience some minor changes have been made to certain of the equipments, but in the main the complete electrical installation is now operating with the minimum of trouble.

Acknowledgments

The author wishes to thank Steel Peech & Tozer for permission to publish this article and reproduce the photographs and diagrams, and also the individual members of that Company and of The English Electric Company who assisted by checking and commenting on the text.

An article describing in more detail the automatic speed controls provided on the new Brinsworth Mill will be published in the March 1959 issue of this Journal.

Design and Construction of the Compressor for the 8 ft x 8 ft High-speed Wind Tunnel at the Royal Aircraft Establishment, Bedford

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This article is an abstract of the Paper presented by the authors to the Institution of Mechanical Engineers on the 28th February 1958. Two articles on this wind tunnel were published in the March and June 1958 issues of this Journal, describing respectively the electrical drives and the electronic speed control.

I. SELECTION OF THE DESIGN

AT THE TIME the design of the Bedford compressor was undertaken there existed in the United States two smaller but comparable compressors for rather simpler wind tunnels, the much larger Tallahoma compressor system being in a moderately advanced design stage. None of these compressors had to meet the range of requirements specified for Bedford, where a single tunnel

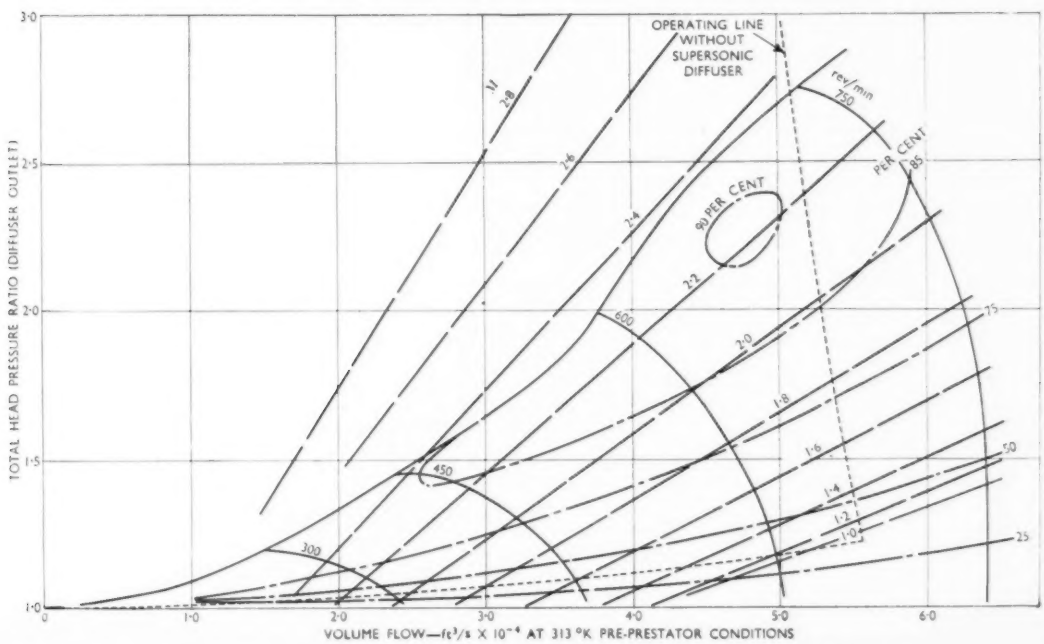

Fig. 1.—*Typical compressor characteristic showing operating line resulting from use of a fixed working section*

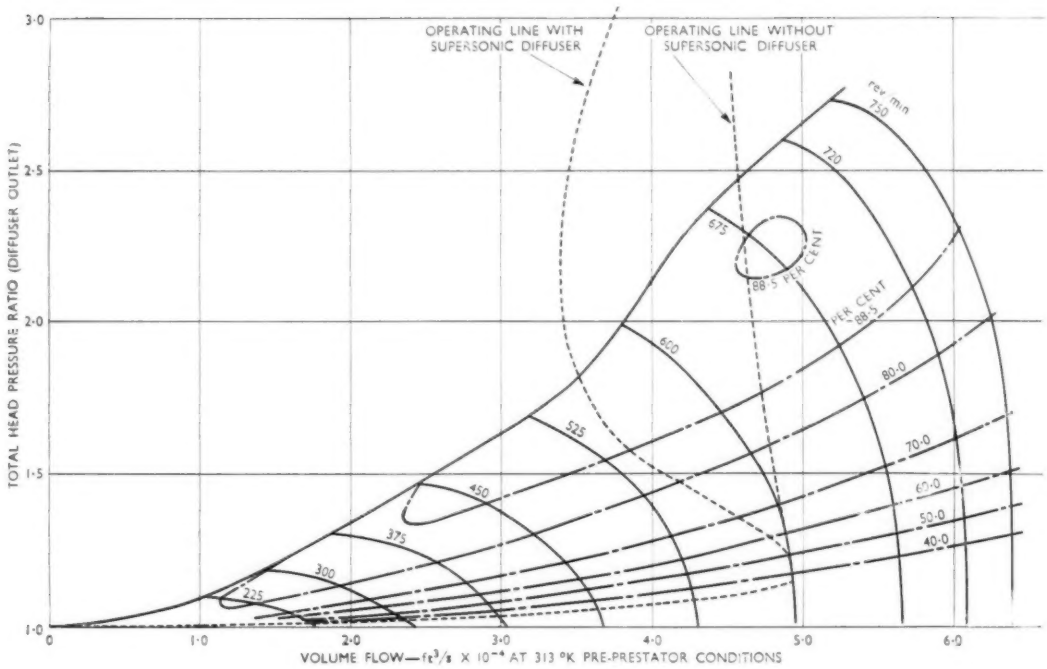

Fig. 2.—Overall characteristic of 10*-stage compressor, Build* 1

was required to deal with low speed, transonic, and supersonic investigations.

With a fixed tunnel working section, the required operating line is of the type shown superimposed on a typical compressor p—v characteristic in Fig. 1. The final specified full-speed requirements were a minimum pressure ratio of 2.5 at about 50,000 cu ft/sec inlet volume flow; it will be noted that the flow remains fairly constant over nearly all the range of pressure ratio, so that the efficiency in the low wind-speed range is only about 30%. At the lower wind speeds especially, the Reynolds number, which depends on air density, is of great importance and the attainable air density for a given power input depends on how much of this power goes into the air as useful work. At 30% efficiency, the required Reynolds numbers could not be attained, and therefore economic methods of improving efficiency in the low pressure-ratio region had to be devised. The low efficiency is essentially due to the fact that the pressure rise of the early stages remains sensibly constant at fixed flow, and if a low overall pressure ratio is called for, the later stages may even have to produce a pressure drop.

Before mechanical design could be considered, it was necessary to decide on the means to be adopted to raise the compressor efficiency at low pressure ratios, and the following possibilities were examined :—

(*a*) Rapid adjustment of rotor blade stagger.
(*b*) Rapid adjustment of stator blade stagger.
(*c*) The provision of variable camber on the stator blades.
(*d*) Varying the number of stages in operation.

Adjustment of rotor blade stagger appeared unrealistic, particularly as rapid operation would be necessary. Adjustable stator blades showed much more promise, approximately doubling the efficiencies of the fixed blade compressor at unity tunnel Mach number. However, in this case, the speed falls rapidly with decreasing pressure ratio; hence the power available from the motors, and consequently the compressor power input, would be

reduced. Despite the improved efficiency, only a small benefit in tunnel pressure level would be attained. The provision of variable camber on the stator blades, a suitable device in some cases, failed with a multi-stage compressor on both aerodynamic and mechanical grounds.

Aerodynamically, the simplest line of attack was to cut out a number of the high-pressure stages during low pressure ratio operation, and attention was concentrated on the best means of doing this. On looking carefully at different methods of by-passing some of the stages, it was finally decided to provide for the complete withdrawal of the H.P. section of the compressor, substituting for it a section of plain annular duct. Although this decision involved special mechanical and structural problems, these were entirely divorced from the aerodynamic design and development work and hence all aspects of the project could proceed together.

The special mechanical problems requiring solution were (1) the design and development of a flexible circumferential casing joint capable of reasonably rapid make and break, (2) the design of a withdrawable flexible coupling, (3) the design of a mounting vehicle or truck for the H.P. section, with gear for moving this truck and for lowering it off the traversing wheels on to solid seatings for H.P. compressor running, and (4) the design of these seatings to incorporate automatic connections for the compressor oil and air services and also to contain a device for providing a substantial clamping force between the truck and the seating.

As to the aerodynamic considerations: although a variable-speed drive was to be provided, it was specified that the compressor should be able to be driven off the Grid electricity supply, so that the choice of speeds was limited to 600, 750 and 1,000 r.p.m. It was finally decided, from consideration of Mach number, blade angles and disc and blade

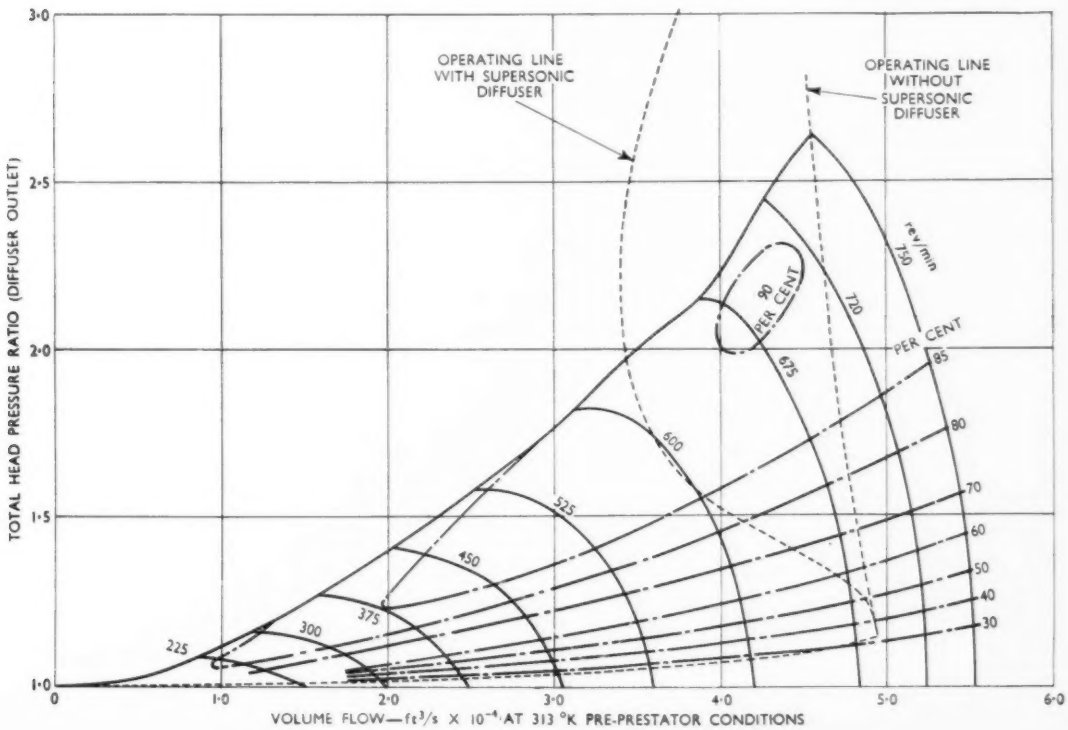

Fig. 3.—Overall characteristic of 10-stage compressor, Build 3

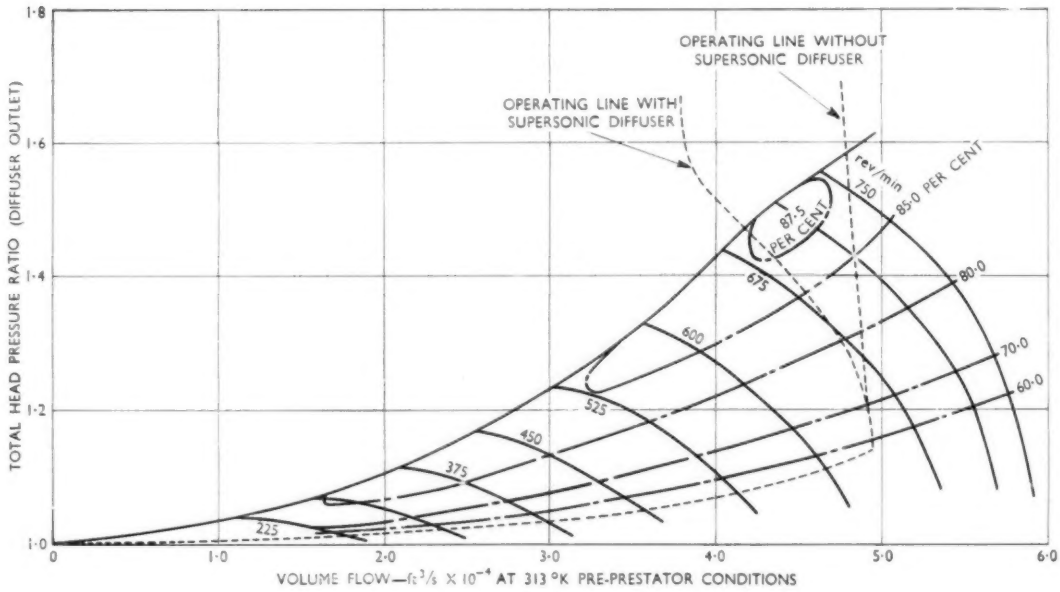

Fig. 4.—Overall characteristic of 4-stage compressor, Build 3a

stresses, to design for 750 r.p.m. using ten stages of constant root diameter. For the blading, it was decided that firstly, the same blade profile design should be used in all stages and that variation of blade length should be obtained by tip cropping, and secondly, that the axial velocity should be progressively reduced through the compressor to reduce the diffuser loss. A ' constant α_3 ' design (a design in which the air angle into the stator is constant and which is roughly midway between free vortex and constant reaction designs) was chosen because it gave least variation of root and tip incidences on the various blade rows. It was also decided to use cantilever stator blades because of doubts about the effect of shrouding on compressor performance.

Steel for the blade material was selected to give maximum assurance of safety against vibration. Wake interferences were carefully considered to avoid excitations of the lower, more dangerous modes, at all but the lowest speeds.

To complete this brief account of the general design basis, it remains only to deal with the part taken in the general plan by the ' model ' or ' test ' compressor. It had been decided at an early stage that an undertaking of the magnitude of the main compressor could not be committed without the provision of a small-scale aerodynamic model: this model would be made only aerodynamically similar to the main compressor; it would have adjustable blades on both rotor and stator, with the removal of the H.P. section of the main compressor simulated by omitting the H.P. blades on the model. Thus from the decisions previously noted on the aerodynamic design, the blades for the main compressor could be put in hand, the stator blades (to be adjustable in the main compressor) complete and the rotor blades up to the stage of root machining. This last operation only would await the results from the test compressor.

Summarising, the aerodynamic design basis was :—

(1) To use one blade-profile design for the rotor and one blade-profile design for the stator (apart from the entry stator blades).
(2) To crop the tips where shorter lengths were required.
(3) To establish by calculation the probable optimum setting of the blades.

(4) To provide adjustment in stator-blade setting.

(5) To make a complete 1/7th scale aerodynamic model, having adjustable rotor and stator blades.

(6) To fix the setting of the rotor blades, by suitable machining of the roots, after the results of the model tests.

(7) To establish for the chosen rotor-blade settings the performance variations resulting from changes of stator-blade setting.

The test compressor amply fulfilled its required role as a design guide, and in addition provided the Royal Aircraft Establishment with valuable data for tunnel performance estimates.

Fig. 2 shows the first ten-stage characteristic obtained, and it will be seen that the blade settings chosen give rather a larger throughput than required. Fig. 3 shows the characteristic obtained from the blade settings finally adopted for the complete ten-stage compressor. Fig. 4 shows the four-stage characteristic obtained with the blade settings as fixed from the final ten-stage build. It will be noted that the efficiency at unity tunnel Mach number is now nearly 60%, i.e. approximately double that obtained with the ten stages in operation. Fig. 5 shows by means of the top 'speed lines' alone, the range of flow obtainable by changing the stator blade settings only.

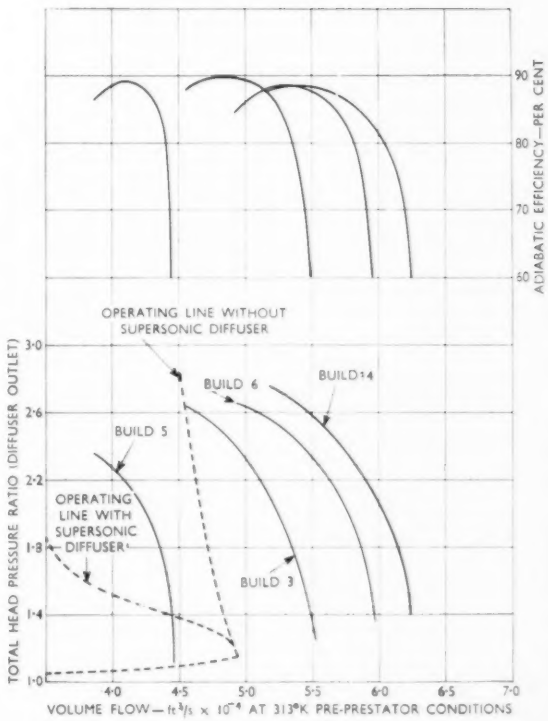

Fig. 5.—Full speed (750 r.p.m.) characteristics of 10-stage compressors, Builds 3, 4, 5 and 6

II. FEATURES IN THE DESIGN AND CONSTRUCTION

Having stated the basic design decisions and the reasons for them, some of the more interesting mechanical features and manufacturing aspects consequent upon those decisions can be discussed.

Fig. 6 shows a sectional drawing of the compressor, from which the location of the parts to be described later can be seen.

The four L.P. stages are permanently coupled to the driving motors through a long propeller shaft, one end of which can be seen at the right of the illustration. The couplings consist of single steel discs (one of which can be seen), one at each end of the shaft to ensure ample flexibility. The rotor is of the disc and ring type and is seen in greater detail in Fig. 7. The position of the flexible casing seals can be seen at the L.P. and H.P. outlets, and the withdrawable flexible coupling, which also forms the intermediate shaft, is shown in the disengaged position. Both L.P. and H.P. casings can be split on vertical joints and withdrawn for blade inspection, and some parts of the casing splitting gear can be seen between the casings and the compressor lubricating oil tanks. The rollers and guide rail of the H.P. truck can be seen, but this illustration does not show much of the truck shifting gear. Fig. 8 is a perspective view of the compressor with the H.P. casing split.

The general scheme for the compressor is shown diagrammatically in Fig. 9.

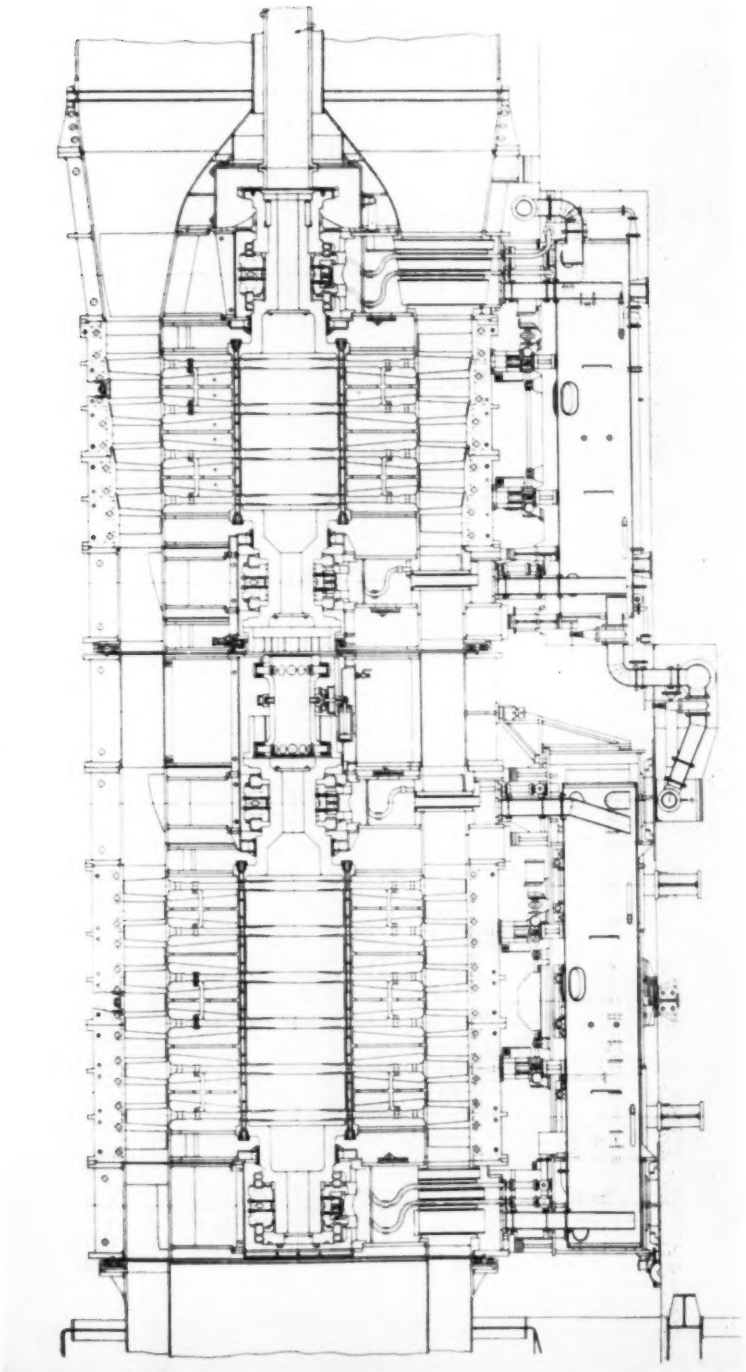

Fig. 6.—Sectional arrangement of compressor

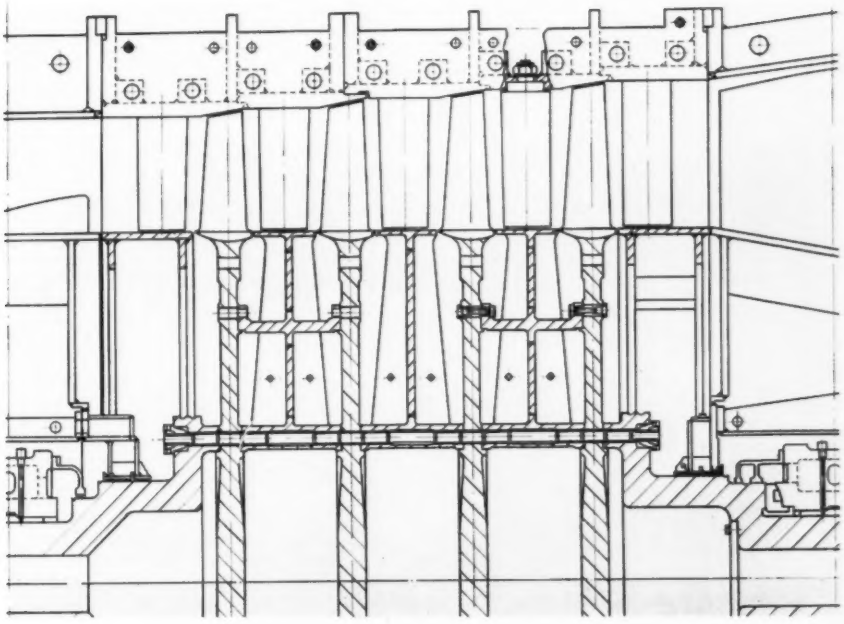

Fig. 7.
Compressor rotor construction

Individual components and features are now described.

Rotors : Construction and Arrangement in Casings

The rotor diameter is 12 ft 3 in. The discs were bolted together in pairs at the works and assembled with the shroud carrying rings on to the stub shafts at site, the whole being bolted together by 24 through bolts in 80 ton C.M.A. steel which were hydraulically tightened to a predetermined stress. This type of construction in the size in question clearly called for somewhat exceptional manufacturing accuracy, and the clock readings actually obtained were quite remarkable, as is shown in Fig. 10. A photograph of the unbladed L.P. rotor is reproduced in Fig. 11.

One of the interesting solutions to problems was that used for removing individual blades as shown in Fig. 12. The blades are held in axial slots having a radial bearing surface, the underside of the blade root being radiused from the same centre; by the rotation of any blade about this centre, it is possible to withdraw the blade without disturbing any other. The longest rotor blade weighs 120 lb and the forging weight was about 450 lb.

As will have been seen from the sectional drawing in Fig. 6, the L.P. and H.P. rotors are each mounted on two journal bearings, and the thrust bearings, which are of the fixed-pad inclined-face type, are at the inlet and outlet ends respectively of the casings which are machined from heavy fabrications.

Lubrication etc.

Since all bearings are buried and no oil must leak into the tunnel air stream (which can vary in pressure from 1/10th to 4 atmospheres) somewhat elaborate arrangements for lubrication, bearing gland ventilation etc. were inevitable, and special attention had to be paid to jacking in view of the heavy weight and high thrust loads. The bearings are of the thin wall type and are supplied with oil from pumps belt driven from a shafting system coupled to the main drive, thus avoiding loss of oil due to electrical failure. A diagrammatic arrangement of the lubrication system which was installed by Denco Engineering Services Ltd is shown in Fig. 13. The bearing gland ventilation system is illustrated in Fig. 14.

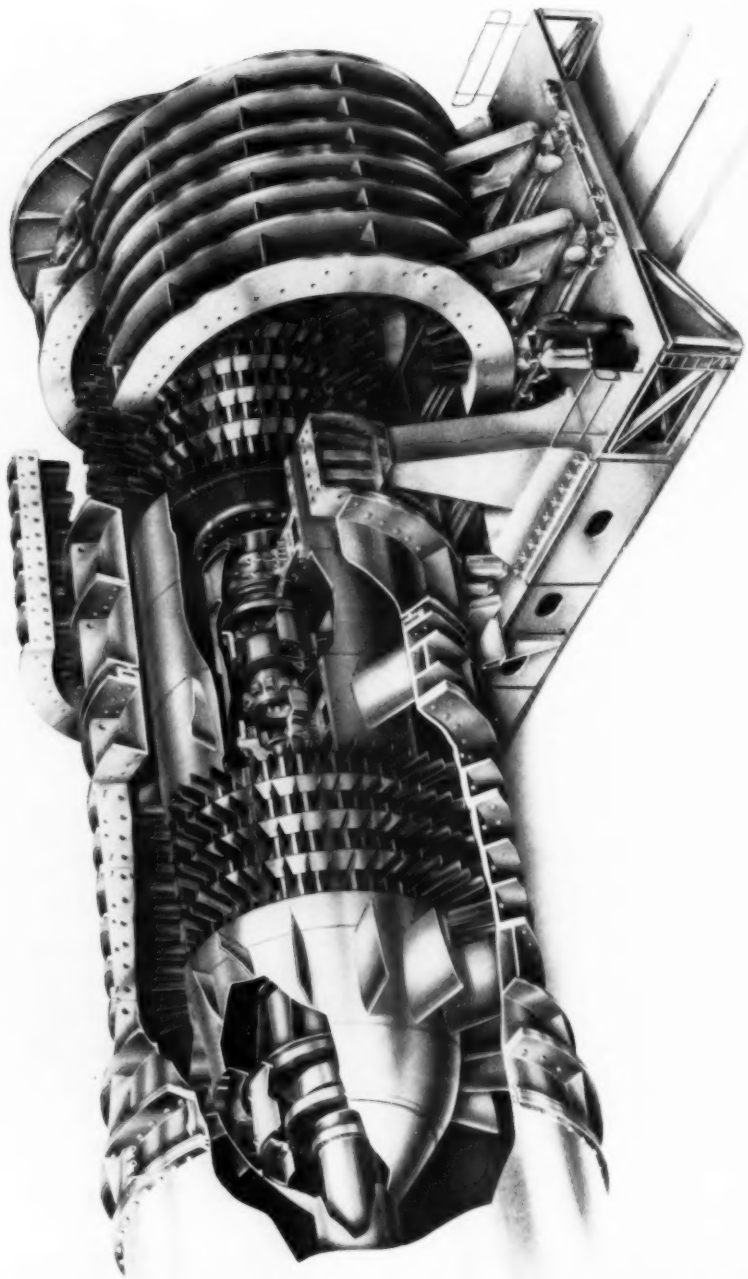

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Fig. 8.—Main compressor for 8 ft × 8 ft high-speed wind tunnel

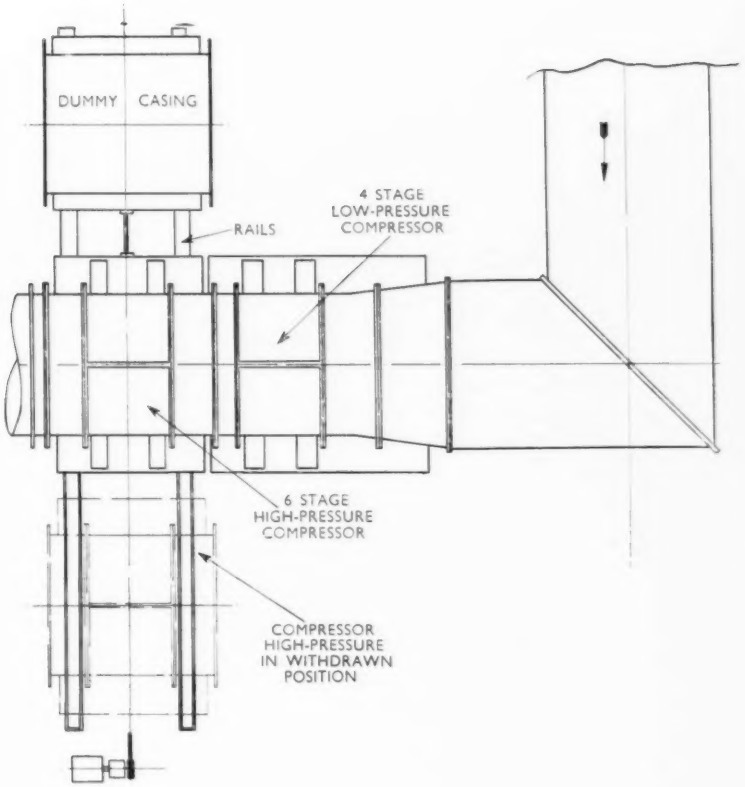

Fig. 9.—Diagrammatic arrangement of compressor

Intermediate Shaft

The floating intermediate shaft, Fig. 16, between the L.P. and H.P. rotors has three duties, namely, to act as a clutch for freeing the H.P. rotor on casing exchange, to take up misalignment between the rotors, and to take up axial expansion of the rotors. The shaft is essentially a development of the tooth coupling widely used for steam turbines. In such couplings with long fixed teeth, torque load will concentrate at the ends of the diameter about which angular misalignment takes place. This effect can be eliminated by mounting the teeth on radial circular pins, but a small residual load concentrating effect remains, reaching a maximum at 45° positions. In the present design, the shaft carries at each end twelve cast iron shoes mounted on radial pins. Between shoe and pin is a bonded pre-loaded rubber bush which under the full-load torque of 400,000 lb-ft displaces radially by about .040 in. These bushes cater for the small load-concentrating effect mentioned, and eliminate wear between pin and shoe.

The shaft is permanently engaged with a long splined hub on the H.P. rotor and can be engaged with and withdrawn from a short splined hub on the L.P. rotor. Fig. 15 shows the shoe-pin-bush arrangement, and the bottom drawing shows how this eliminates the unsatisfactory kinematic properties which show up on this type of coupling when there is significant misalignment. Location during running is through a thrust collar on the shaft; a spring-mounted combined thrust and journal carrier ring transmits the required movement to the shaft from a hydraulic cylinder.

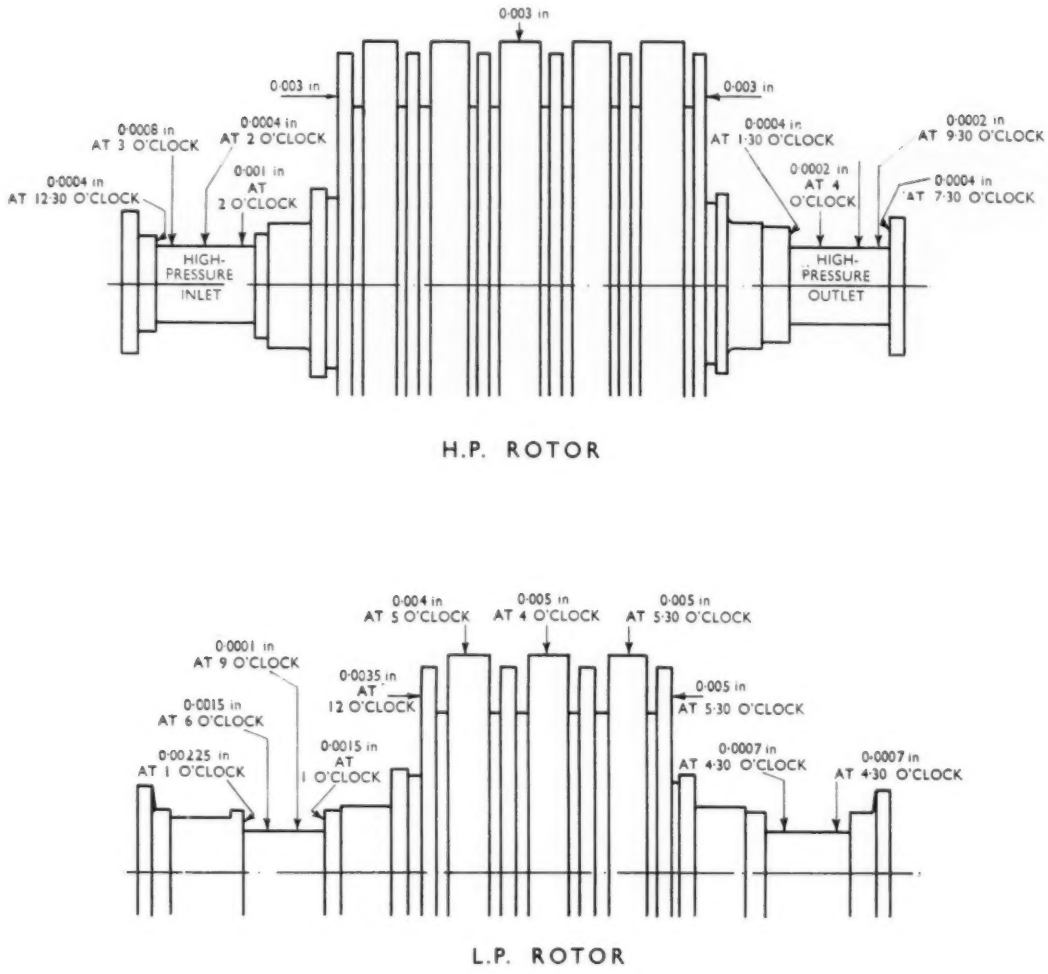
0·003 in
0·003 in
0·003 in
0·0008 in AT 3 O'CLOCK
0·0004 in AT 2 O'CLOCK
0·0004 in AT 12·30 O'CLOCK
0·001 in AT 2 O'CLOCK
0·0004 in AT 1·30 O'CLOCK
0·0002 in AT 9·30 O'CLOCK
0·0002 in AT 4 O'CLOCK
0·0004 in AT 7·30 O'CLOCK
HIGH-PRESSURE INLET
HIGH-PRESSURE OUTLET
H.P. ROTOR
0·004 in AT 5 O'CLOCK
0·005 in AT 4 O'CLOCK
0·005 in AT 5·30 O'CLOCK
0·0001 in AT 9 O'CLOCK
0·0035 in AT 12 O'CLOCK
0·005 in AT 5·30 O'CLOCK
0·0015 in AT 6 O'CLOCK
0·00225 in AT 1 O'CLOCK
0·0015 in AT 1 O'CLOCK
0·0007 in AT 4·30 O'CLOCK
0·0007 in AT 4·30 O'CLOCK
L.P. ROTOR

Fig. 10.—Actual errors in rotors at completion of assembly

Main Casing Seals

It was decided to obtain the necessary flexibility in the seals by the use of rubber in shear, and Fig. 17 shows the design adopted which consists of a floating steel ring connected to two flange rings by natural rubber sections, which are rubber bonded to the steel parts. The flange rings are bolted to a fabricated channel-section steel ring. Pressure from a water circuit (which also cools the seal) is applied inside this, forcing the floating ring forward against a sealing strip in the mating flange; the resilience of the rubber pulls the seal clear on the release of pressure. These rings must be one of the largest examples of bonding so far in existence, and involved an extensive programme of development undertaken in collaboration with the Andre Rubber Company Ltd. The final moulding and bonding operation involved applying

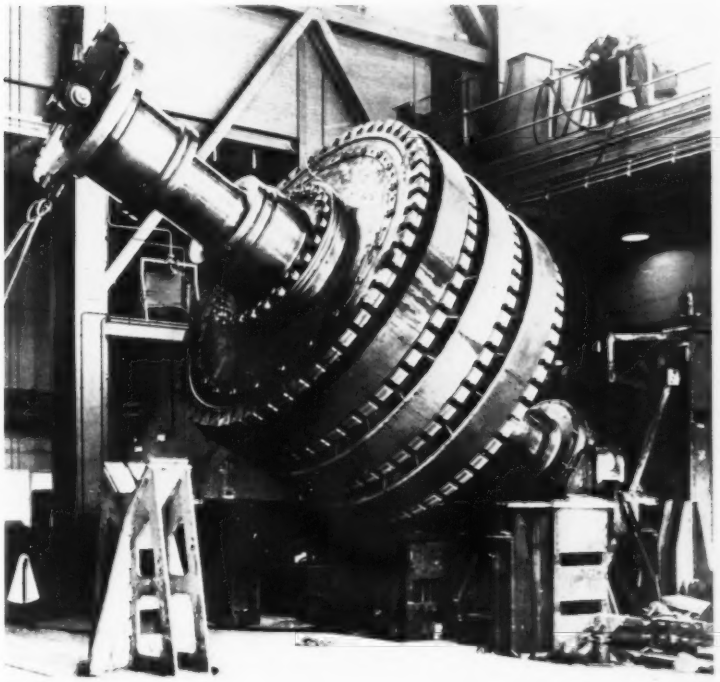

Fig. 11.—Unbladed L.P. rotor being lowered to horizontal position

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heat and pressure to the rubber for several hours. The moulds were fitted with electrical heating, with adequate provision for temperature control. Twenty-four hydraulic jacks (Fig. 18), each giving 55 tons thrust, clamped the mould portions and maintained a pressure of 700 lb/sq inch in the rubber.

H.P. Truck and Compressor Shifting

Perhaps the most interesting crop of design problems related to the alternate securing and moving, under closely controlled conditions, of the H.P. section on its truck (weighing some 600 tons) and the associated dummy casing.

The H.P. compressor is mounted on a rectangular truck on to which the compressor pedestals are bolted. The main truck members are about 4 ft 6 in deep.

For H.P. compressor running, the truck rests on seatings in the foundations and is raised on to its

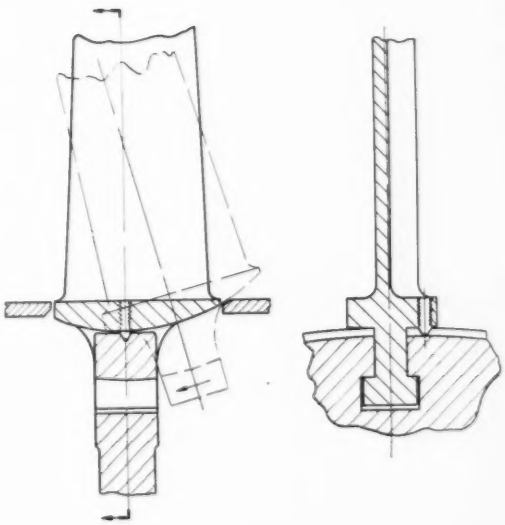
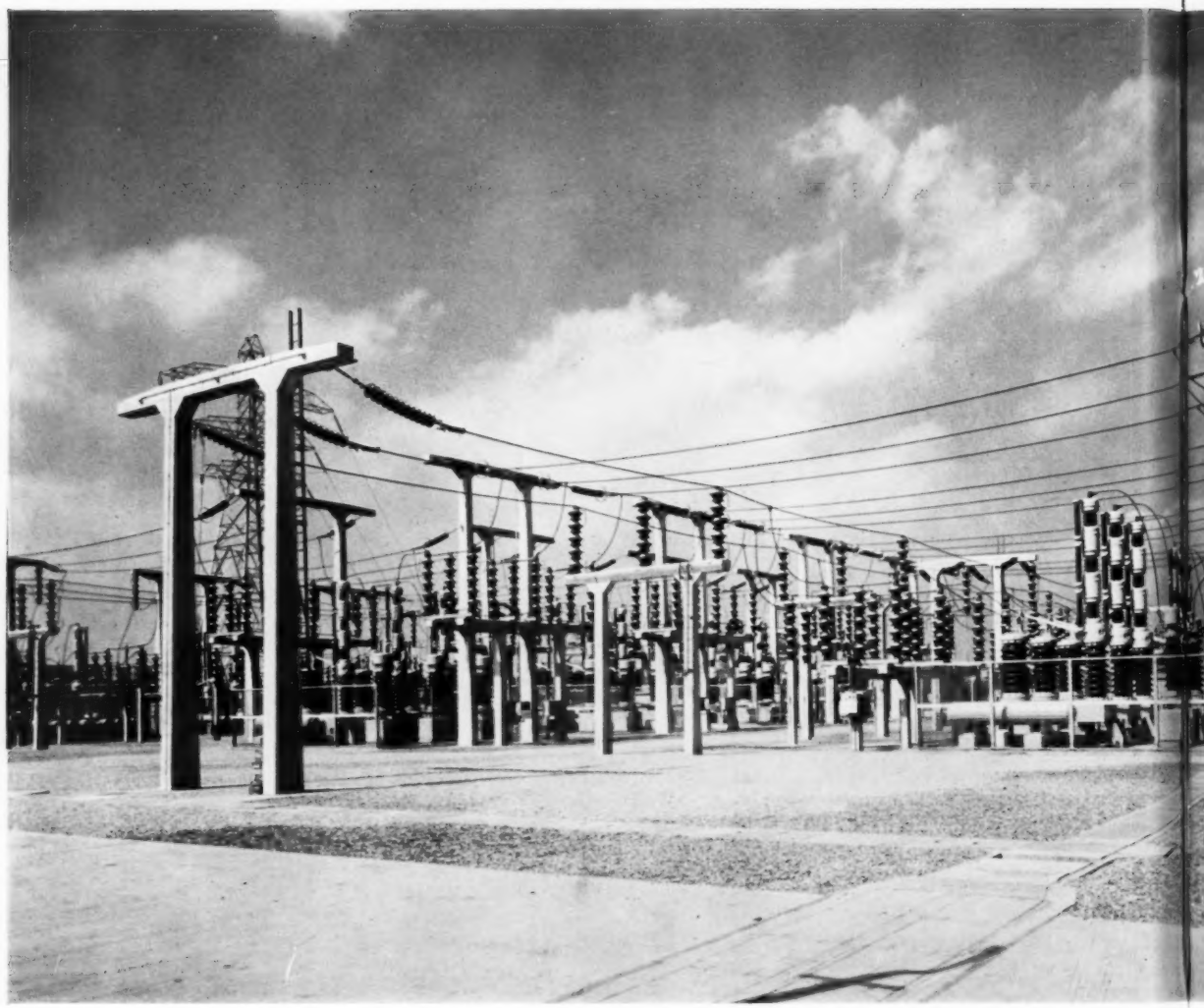
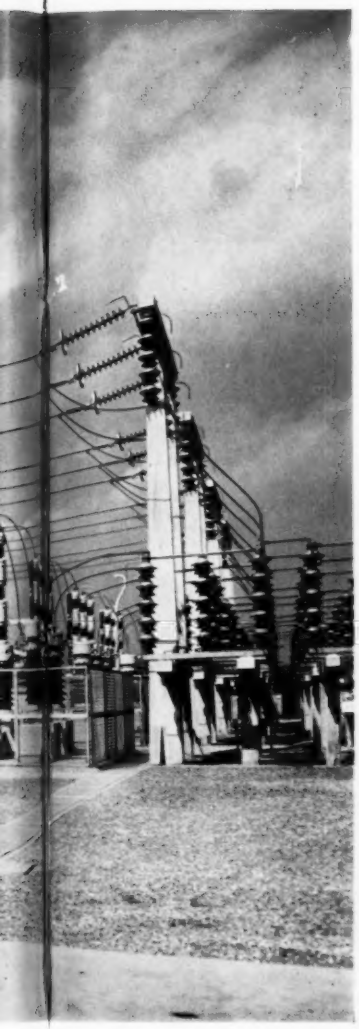


Fig. 12.—Individually removable compressor blades

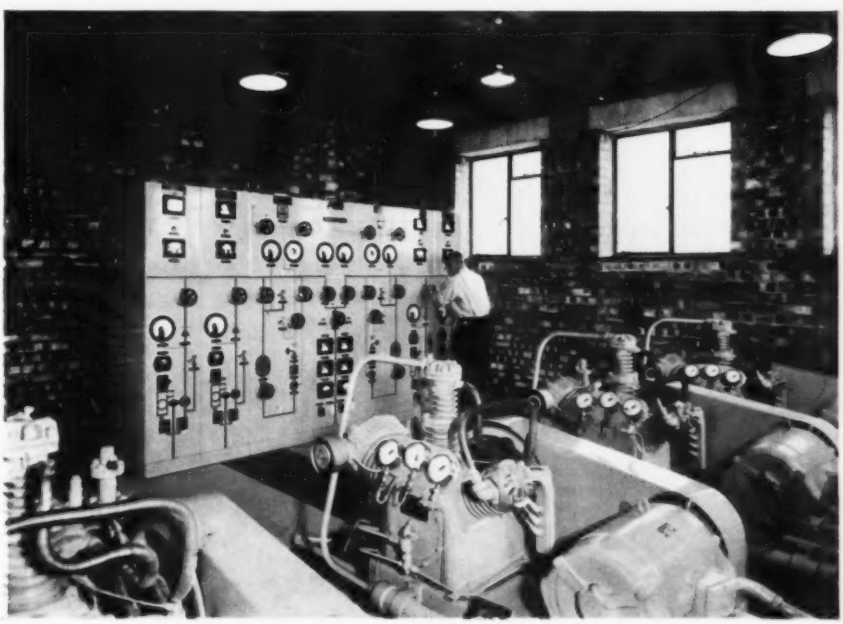


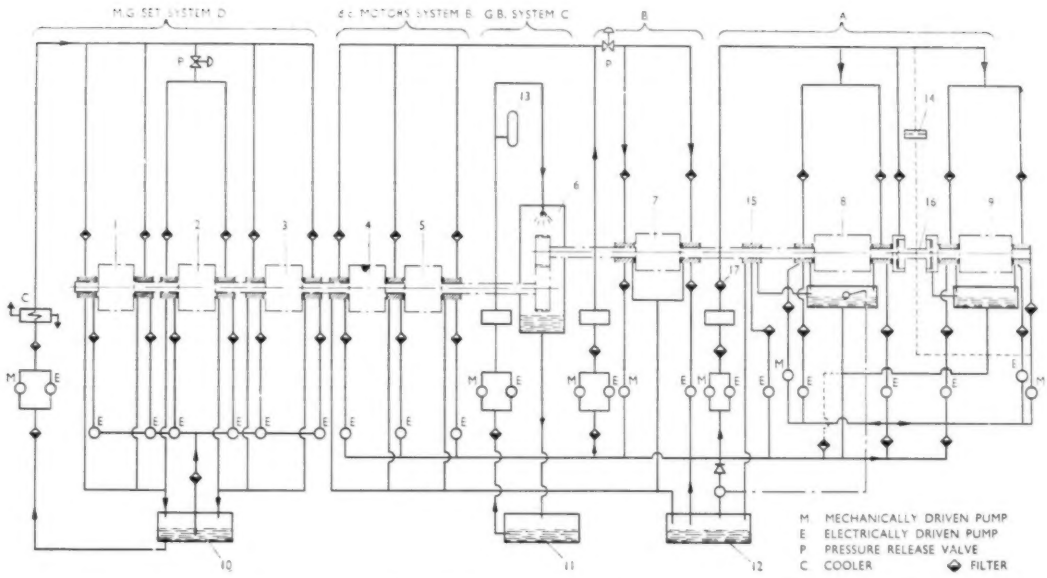
Capenhurst 'D' substation of the Central Electricity Generating Board, North West, Merseyside and N Region, incorporating eleven 132 kV 3500 MVA 'English Electric' air-blast circuit-breakers with the associ isolators, current-transformers and voltage-transformers, and a 16-panel control and relay board.



de and North Wales
the associated 132 kV
lay board.

The compressor house at Capenhurst 'D' substation, with the compressor units in the foreground and the distribution board in the background.





1. 6,000 h.p. d.c. generator
2. 14,000 h.p. induction motor
3. 6,000 h.p. d.c. generator
4. 6,000 h.p. d.c. motor
5. 6,000 h.p. d.c. motor
6. Speed-increasing gearbox
7. 68,000 h.p. synchronous motor
8. 4-stage L.P. compressor
9. 6-stage H.P. compressor
10. Oil reservoir, System D
11. Oil reservoir, System C
12. Oil reservoir, Systems A & B
13. System C air vessel
14. H.P. section bypass orifice
15. Shaft seal
16. Intermediate shaft
17. Magnetic filter

Fig. 13.—Schematic arrangement of lubrication system

A. Bellows seal
B. Dummy rotor
C. L.P. oil tank
D. L.P. inlet
E. Intermediate section
F. Tunnel
G. H.P. rotor
H. L.P. rotor
J. L.P. oil tank
K. H.P. oil tank
L. Balance pipe giving reverse flow at low pressure ratio
M. Cooler
N. Cotton-wool filter
O. Oil separator
P. Non-return valve
Q. Orifice controlling flow above 17.8 lb in^2 abs tank pressure
R. Oil separator
S. Manual valve locked shut when vacuum pump is running
T. Automatic valve closing when tank pressure rises to 17.8 lb in^2 abs
U. Pressure-operated switch stopping pump when tank pressure rises to 17.8 lb in^2 abs
V. Vacuum pump controlling flow below 17.8 lb in^2 abs

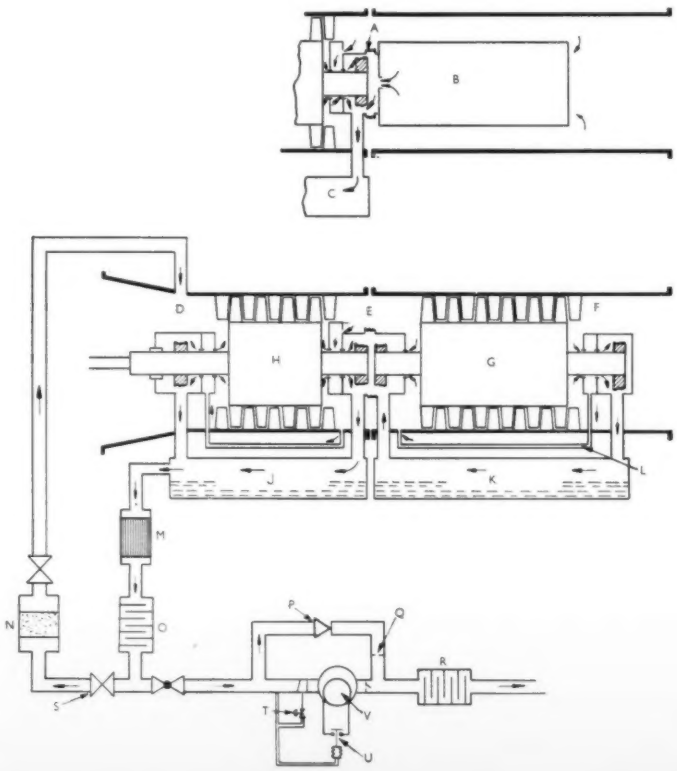


Fig. 14.–Bearing ventilation system

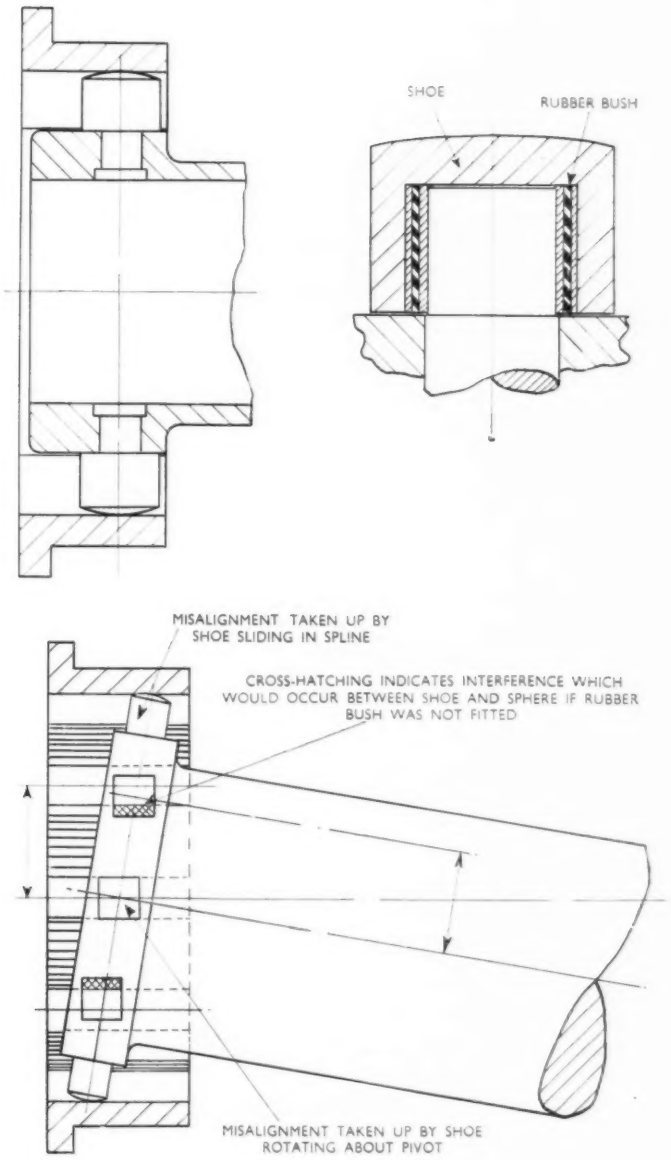


Fig. 15.— Intermediate shaft, showing principle of operation

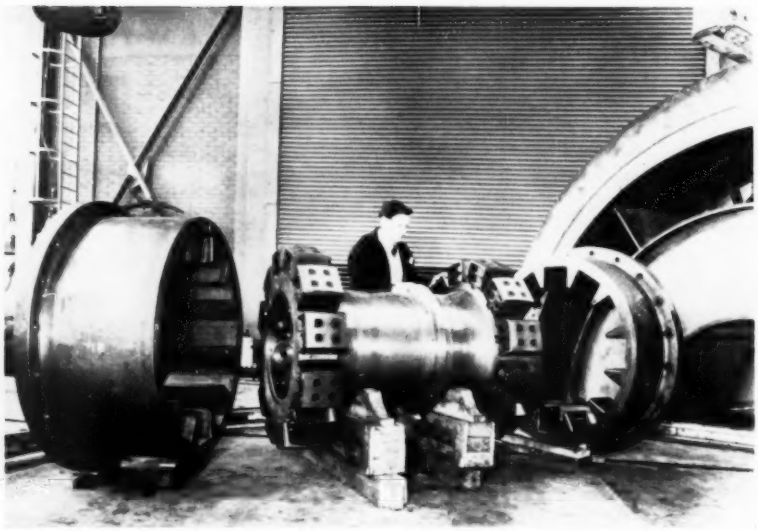


Fig. 16. — Intermediate shaft

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wheels for H.P. compressor/dummy casing interchange. This truck, of course, carries the rails for bladed casing splitting. For compressor interchange, the truck is raised by 1 inch (of which $\frac{1}{2}$ inch is clearance and $\frac{1}{2}$ inch represents movement to actuate automatic oil valves) by two hydraulic cylinders each coupled to four wheels. The method of raising and lowering the truck is shown in Fig. 19. The double-ended piston of the jack is secured to the truck and the cylinder moves downwards for lifting, forcing outward two toggle arms, each actuating a pair of wheels.

The movement of the cylinder past the top dead centre position of these arms obviates the need for maintaining oil pressure to keep the truck raised. The outward movement rotates the lever arm from which torsion bars run to each end of the truck, operating a further lever system which forces the wheels downwards. The wheels are 12 inches wide, having a line loading of 28,000 lb per inch, and to ensure uniform load distribution are on large diameter spherical hubs which rotate on roller-bearing support spindles. A jacking control valve ensures the correct porting for oil flows and sequence of operations for raising or lowering. The truck is moved at a maximum speed of 6 ft per minute by a slipring induction motor which drives a vertical pinion engaging a long rack on the side of the truck through a spur and worm gearbox.

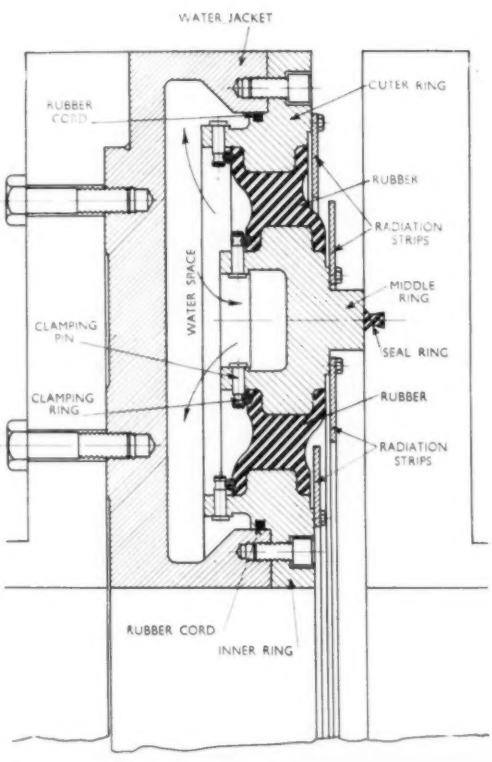

Fig. 17.—Section through main casing air seal

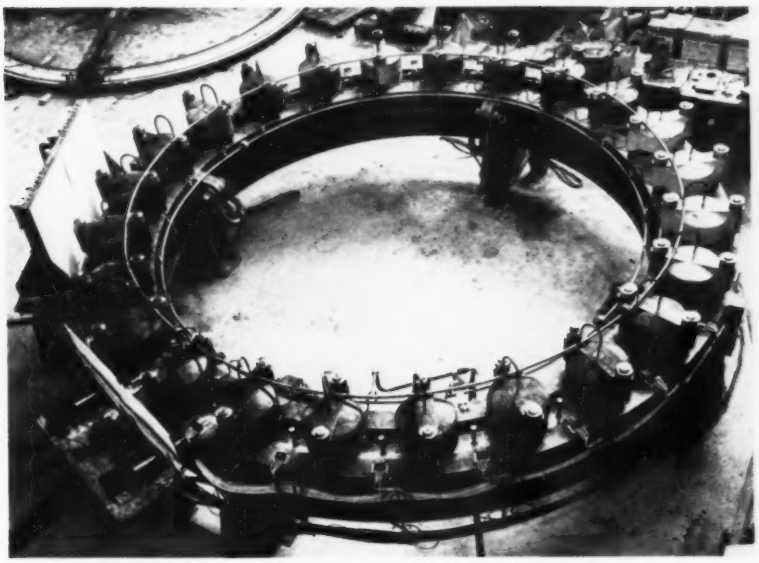

Fig. 18.—Moulding of main casing seal

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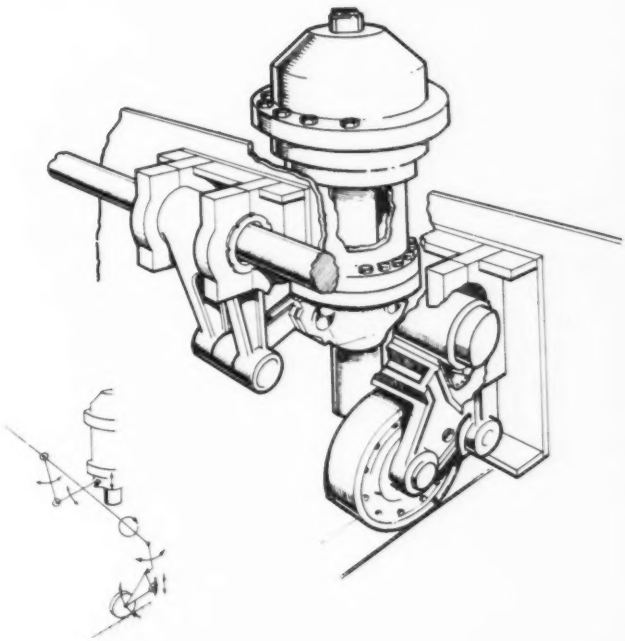


Fig. 19.—H.P. truck jacking system

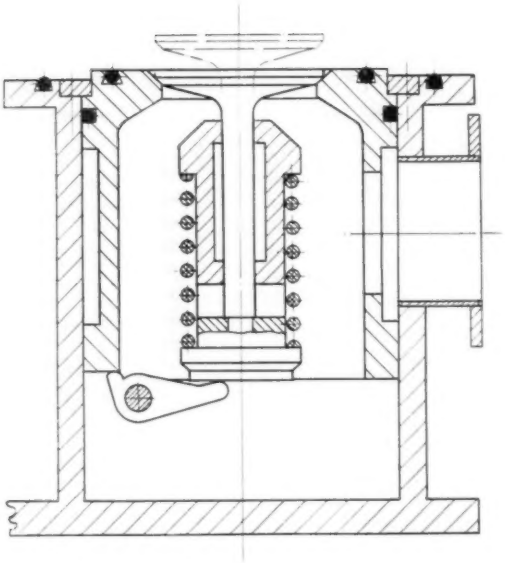


Fig. 20.—Oil supply and drain valves

The truck carrying the dummy casing is similar to the H.P. truck, but with a load of only 96 tons, only four wheels are necessary. It is coupled to the H.P. truck by a solid drawbar.

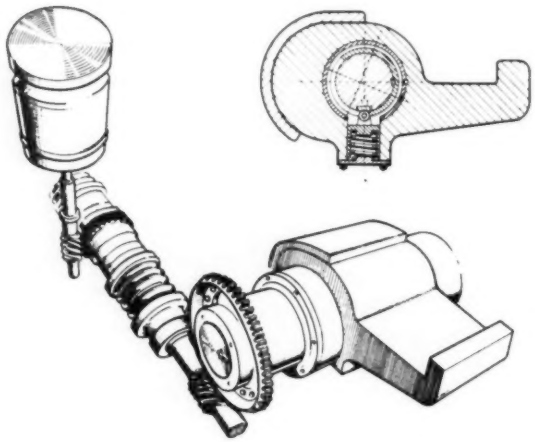
In the operating position, the H.P. section is supported and secured by four fabricated boxes bolted to grillages in the concrete foundations. These boxes contain oil supply and drain valves and gear for clamping the faces beneath the trucks on to the top surface of the boxes. The large oil supply and drain valves open when the downward movement of the truck is applied to the outer sleeves as shown in Fig. 20.

The clamping mechanism in each box consists of two counterweight hooked arms, Fig. 21, driven by detents from rotating shafts, each having an eccentric position in the bore of the hooked arm. When the rotation of the arm is arrested by the edge of the sealing face, the detent breaks out and continued rotation of the shaft causes the eccentric to pull the arm downwards into contact with the lip projecting on each side of the seating.

Compressor Splitting Control System

A comprehensive sequencing and interlocking system has been provided to eliminate any possibility of damage which could occur due to incorrect operation as, for example, by attempting to raise or move the truck with the intershaft engaged or the casing seals closed. The heart of the interlock and control system is an electro-mechanical sequencing table which prevents the initiation of an action until the satisfactory conclusion of the preceding action. The operation of splitting the compressor and substituting the dummy casing can be completed by one operator in 20 minutes.

Fig. 21.—Truck clamping gear



British Hydro-Electric Plant and World Power Requirements

By J. C. BEVERLEY, M.A., A.M.I.Mech.E., A.M.I.E.E., Contracts Manager, Hydro-Electric Department, E. G. TEASDALE, B.A., Sales Manager, Hydro-Electric Department, and A. WILMOT, B.Sc.Tech., D.I.C., A.M.I.Mech.E., Chief Project Engineer, Water Turbine Department.

PART II

Part I of this article was published in the September 1958 issue of this Journal, volume fifteen, number seven, page 3.

THE EFFECT OF MODERN TRENDS ON ALTERNATOR DESIGN AND CONSTRUCTION

Design Criteria

Before the period under review, 1944 to the present date, in the main the limitations and requirements of the alternator design did not have any significant effect on the basic design of the turbines, and apart from the special characteristics of required flywheel effect and ability to withstand maximum turbine runaway speed, the machine could be looked upon as a more or less normal alternator.

The increasing size of machines required, the extensive interconnection of networks with long transmission lines, and the ever-present economic limitations have all been reflected in the development of water-wheel-driven alternators.

Output Limitations

It is accepted that the machines manufactured

TABLE IV

WATER-WHEEL ALTERNATORS OVER 60 MVA RATING SUPPLIED OR UNDER CONSTRUCTION BY BRITISH MANUFACTURERS

Name	Country	Type	Number of units	Rating in MVA per unit	Speed r.p.m.	Total thrust load tons	Retor diameter inches	Stator core length inches
Bersimis I.	Canada	V.T.B.	4	138	277	496	205	105
Kemano	Canada	V.T.B.	2	132	327	430	194	97
Kariba	Rhodesia	V.U.	6	111	166·7	677	309	77
Bhakra	India	V.T.B.	5	100	166·7	853	268	85
Priest Rapids	United States	V.U.	10	95·5	85·7	1,600	418	58
Belesar	Spain	V.T.B.	3	88	214	500	240	65
McNary	United States	V.T.B.	2	85	85·7	1,740	421	64
Ffestiniog	Wales	V.T.B.	4	78·9	428	310	145	92·5
San Esteban	Spain	V.T.B.	4	75	214	520	222	85
Eildon	Australia	V.T.B.	2	66·6	150	552	310	50
Aura	Norway	H.	3	62·5	428	—	* 127	100
							136	95
Los Peares	Spain	V.T.B.	3	62·4	214	400	211	70
Rihand	India	V.U.	5	61	150	320	298	42
Cabril	Portugal	V.T.B.	2	61	214	406	207	75

* *This station contains machines of two different British designs.*

V.T.B. Vertical two-bracket. *V.U. Vertical umbrella.* *H. Horizontal.*

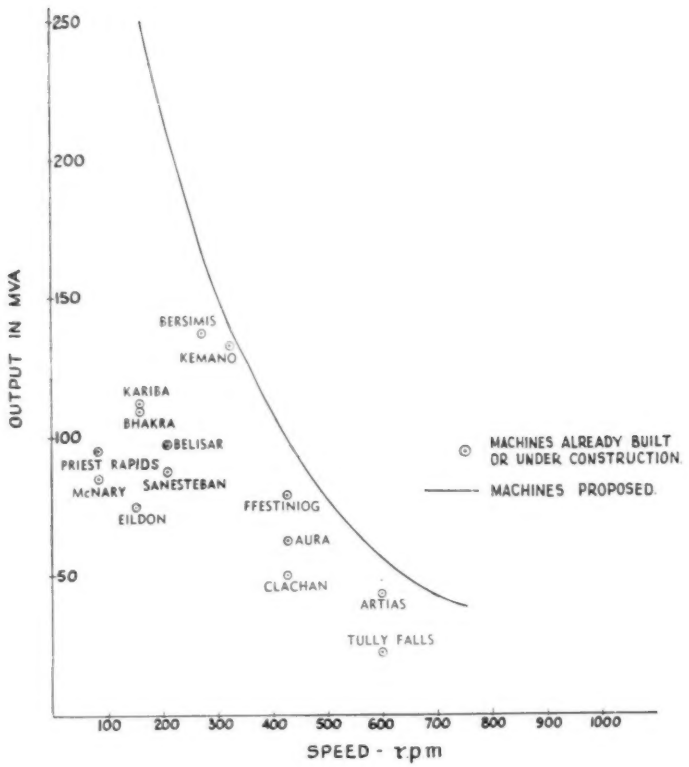


Fig. 24.—Water-wheel alternators : outputs for various speeds

up to the present date have not yet reached the maximum possible output for the speed and conditions chosen, although several projects not yet executed have been reviewed for which this would be the case. Table IV gives some of the important alternators manufactured or in course of manufacture in Britain in the post-war years, and this can be compared with Fig. 24 which shows the outputs for which alternators have been proposed at various speeds. This does not necessarily represent the maximum output for the particular speed. There has been no call for hydrogen-cooled machines, which would increase the limiting output, except for synchronous condensers, which are sometimes required in connection with hydro-electric schemes, and in which the running losses must be kept as low as possible.

The ultimate output for a particular set of conditions is fixed in most cases by the ability to provide adequate ventilation for the stator and rotor to keep them within the prescribed temperature limits. In order to extend the output beyond the normal limits special materials and forms of construction can be resorted to but these are expensive. Also for the higher speeds the mechanical design of the rotor may well become limiting, or the first critical speed may be reached. Fig. 25 shows on a cumulative basis the total orders for water-wheel alternators placed in Britain since 1935.

Stator

The changes in the design of the water-wheel alternator stator have not been spectacular apart from the increase in size, which may involve the splitting of the stator into up to six or more sections to meet transport limitations. The size has however been forced upwards not only by increase in output but also by the stringent requirements of line-charging capacity, or short-circuit ratio, or transient reactance, laid down to meet the transmission system characteristics. The increase in these factors has often swallowed up the saving which would result from improved designs and the lagging power-factor specified. However, the use of a network analyser to study system conditions has contributed towards the more accurate determination of the required alternator characteristics.

To take a recent example, a short-circuit ratio of 1·9 and a lagging power-factor of 0·95 were specified. If the former were reduced to a more normal value of say 1·0 the same size of machine would give an increased output of 25 per cent. If the latter were reduced to the value of 0·8, which was often specified in the past, with the short-circuit ratio reduced to 1·0, the output would only be about 20 per cent. higher. These figures would vary according to other characteristics but they

indicate the importance of careful selection of short-circuit ratio and power-factor.

The successful use of grain-oriented steel for building transformer cores has caused consideration to be given to the use of the same material for stator laminations. The advantages for an alternator are clearly not nearly so marked as for a transformer, since the flux paths in an alternator core must cut across the grain either in the tooth or in the back of the core according to the direction of orientation chosen. There has however been some improvement in the availability of low-hysteresis-loss steel suitable for alternator stators, and increasing use is being made of this material. For instance, it is being incorporated in the four 78·9 MVA motor/alternators for Ffestiniog.

Main Shaft

The large sizes of machine now required have resulted in shaft forging sizes outside the range of many forgemasters. Furthermore, a low-speed and therefore large machine is often driven by a Kaplan turbine which means that a hole is required down the centre of the shaft of the order of 15 inches diameter, but this is sometimes a blessing in disguise as the shaft has to be designed for this condition and the forgemaster can remove impurities which may extend to this diameter in a large forging. The size of forging is kept to the minimum practicable by subdividing the shaft and using a separate shrunk-on thrust collar. These steps however increase the cost of the finished machine due to the additional machining and material required for couplings. A balance has to be struck between these costs and the increased cost of the forging if it is unduly large.

Rotor

The majority of medium and large water-wheel alternators today have rotors of the chain-rim type. The salient poles are supported on a rim built up of steel laminations and carried on a fabricated hub, which may take various forms. The construction affords considerable scope for manufacturers to use ingenuity and to make advances in design.

The basic factors which have to be taken into account in the design of a rotor for a given speed and output are :—

(*a*) Maximum runaway speed
(*b*) Flywheel effect required for turbine regulation
(*c*) Transport limitations
(*d*) Works manufacturing limitations
(*e*) Ventilation.

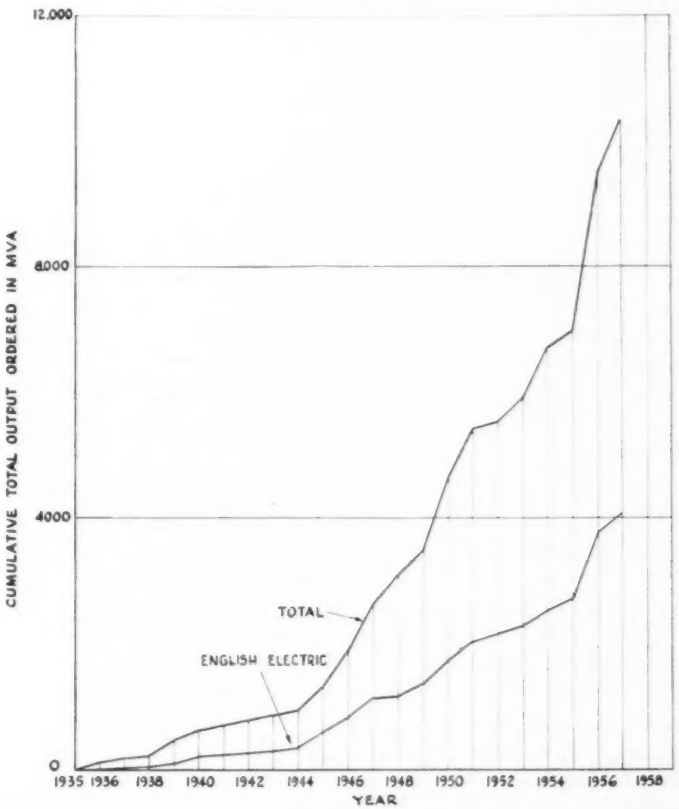


Fig. 25.—Total orders for water-wheel alternators in Great Britain since 1935

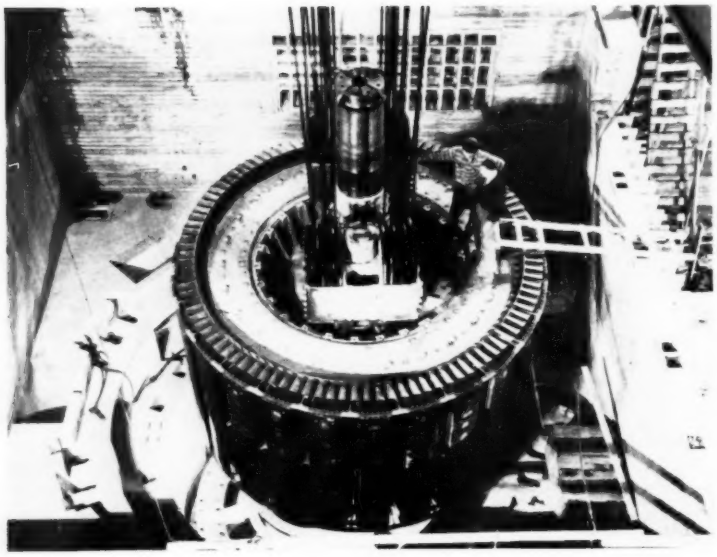


Fig. 26.—Rotor for Bersimis alternator (Metropolitan-Vickers)

The first three can vary widely from station to station and the fourth varies among the different manufacturers, and it is therefore obvious that there will be found much variety among machines in the rotor design. The maximum runaway speed as determined by the characteristics of the turbine runner is calculated on the assumption that the turbine guide vanes are fully open and that there is no electrical load on the alternator, but the calculations should also take into account the increased windage and friction losses at the runaway speed. With a variable-blade turbine such as a Kaplan the maximum runaway speed may occur with the guide vanes in an intermediate position due to the variation in the runner-blade angle, but a further consideration has to be taken into account and that is the speed which may be attained if not only the eventualities stated above exist but also the relationship of the blades to the guide vanes is incorrect to the worst possible extent. Because this eventuality is extremely remote it is now usually considered necessary only to ensure that the elastic limit of all components is not reached under this condition and not to apply any additional factor of safety.

The flywheel effect required is again a factor determined by the turbine, in this case in relation to the hydraulic layout of the tunnel and pipeline and to the allowable pressure and speed rises on rejection of load. The majority of machines now operate on a large interconnected system and significant savings can be made by relaxing the flywheel effect requirements if the flywheel effect cannot conveniently be incorporated in a reasonable rotor design, at the expense of the sacrifice of a certain amount of stability if the machine is ever called upon to run isolated.

The common way to deal with the five factors (except the first) is to concentrate as much weight as possible on the periphery of the rotor, and this automatically leads to the laminated-rim type, which would now be adopted wherever possible instead of a rotor built up of solid plates in which there is an appreciable weight of steel contributing little to the flywheel effect. As an example of this change two vertical alternators rated at 132 MVA 327 r.p.m. were supplied from Britain for the Kemano power station of the Aluminum Company of Canada. The plates used for the rotors of these machines were approximately ten inches thick but such plates would not now be obtainable and a redesigned rotor using a fabricated hub with a laminated rim would result in a saving in weight of 10 per cent.

Improved cooling of the rotor coils can be obtained by fabricating them instead of bending copper strip on edge. This makes it easier to produce a coil with staggered turns and also the increase in resistance due to cold working is eliminated.

The scope given to the designer of a built-up rotor has opened up a field in which still further savings can be made, for instance, cast-steel centres

can be replaced by fabricated centres with box-section arms, or for the smaller diameters, such as the 170 inches of a recent example for Turkey, by single fabrications. Any weight saved on the hub is doubly worthwhile, because dead weight, such as that involved in unnecessary joint flanges, has to be supported by additional weight in parts nearer the axis of the rotor. Typical designs for various types of rotor can be seen in the cross-sectional drawings included in the Appendices, and Fig. 26 shows the rotor for Bersimis.

Bearings

The most noteworthy bearing in a vertical hydro-electric generating set is the thrust bearing, which has to carry not only the weight of the alternator and turbine rotating parts but in addition the hydraulic thrust arising from the passage of water through the runner, which in the case of a Kaplan turbine is particularly large. Some typical values of recent bearing loads are given in Table IV, and Fig. 27 shows the upper bracket for supporting the thrust bearing of the McNary alternator where the load carried is 1,740 tons.

For many years low-speed large-diameter alternators have been designed with the thrust bearing below the rotor. With this arrangement the span of the thrust-supporting members is reduced and it becomes a more simple matter to design the stator frame, which would otherwise have to transmit the load to the foundations. For these reasons this arrangement has grown in popularity. In addition it permits a reduction in the crane-hook height. The range over which it can be used has been extended by the addition of a light guide bearing above the rotor when the rotor core is long. Two 41·7 MVA machines of this type have just been commissioned in the Indian Central Government station at Hirakud. Consideration is also being given to mounting the thrust bearing in the turbine top cover or to supporting the thrust bearing, located below the rotor, by a conical structure mounted directly on the turbine.

The bearing pads are invariably white-metal lined but there are various schools of thought about the degree of polish required on the thrust-collar face, ranging from a mirror finish to a hand-scraped surface. The maximum allowable loading for this type of bearing has been increasing : at one time 400 lb/sq in. was a normal value but 600 lb/sq in. is now frequently used, and the pressure may go still higher. The main advantage resulting from this is the reduction of the radial depth of thrust collar required with consequent saving in the shaft forging and bearing-support structure.

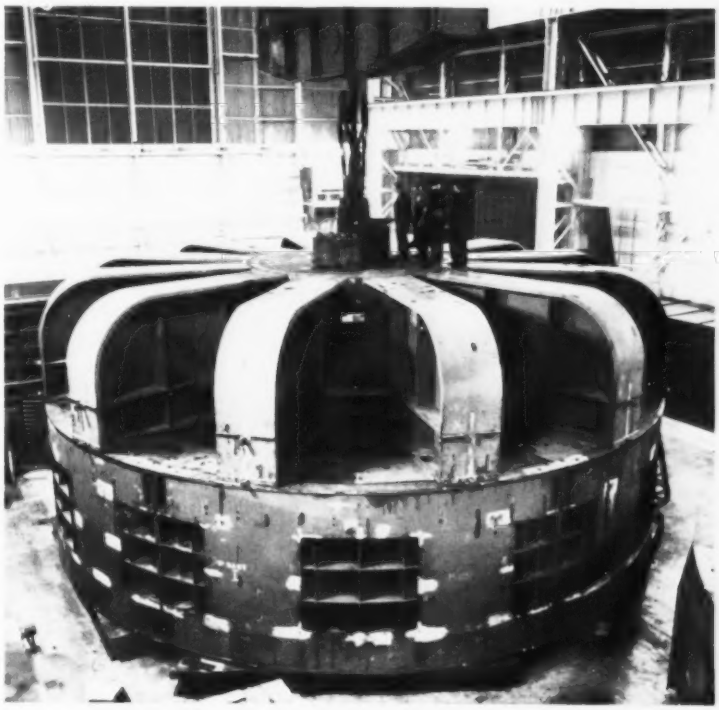


Fig. 27.—Upper bracket and stator for McNary alternator (English Electric)

No special arrangement is necessary for building up the oil film on the bearing pads when starting-up after a short shut-down, but high-pressure oil jacking is added to the bearing for the largest sizes and for machines for pumped-storage operation. In this latter application dual rotation with a minimum of starting torque is necessary when a reversible pump turbine is used, as at Niagara.

Arrangement of Machine

The design of a large water-wheel alternator can influence the cost of the civil works substantially. Gone are the days when the turbine, the alternator, and the exciter were piled up one on the other to form a tower with little regard for overall height. With the advent of underground power stations where each foot means additional excavation in rock, and of heavy machines involving large overhead cranes and substantial buildings, any saving in height is welcome.

The first step was the ' nesting ' of the main and pilot exciters as seen in Fig. 28, and now the introduction of modern high-speed voltage regulators has made it possible to eliminate pilot exciters altogether.

Next, rearrangement of the shafts can sometimes be resorted to as in the case of the 40 MW hydro-electric machine in the underground station at Clachan in Scotland where the turbine shaft runs through the turbine bearing and the alternator lower guide bearing to couple direct on to the alternator rotor shaft. This reduces the headroom required to withdraw the rotor from the stator, which is particularly important for this underground station.

Induction Generators

Although not involving anything spectacular in MVA rating a considerable increase has been made in the use of induction generators in the last ten

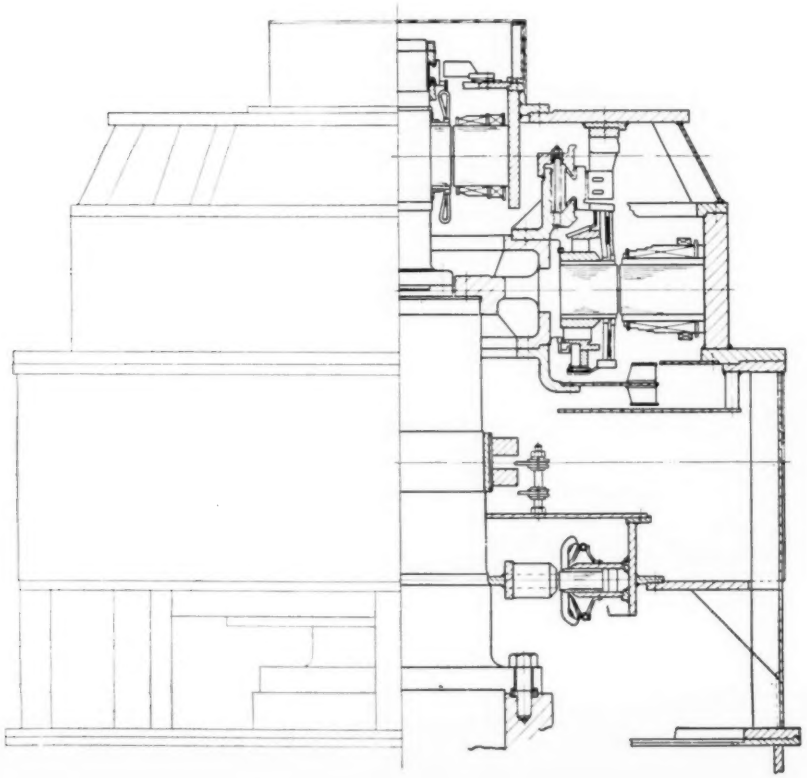


Fig. 28.—Arrangement of 'nested' exciters

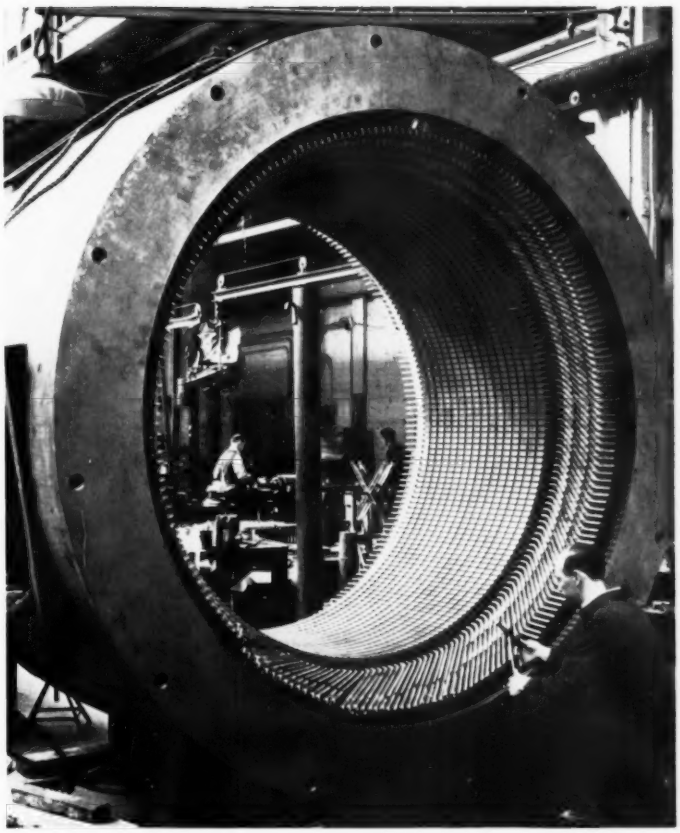


Fig. 29.—Stator for induction generator (Bruce Peebles)

of the old river would be dried up but for the compensation water, and if, as sometimes happens, the station is placed in an adjacent valley the need for compensation water is even more pressing. Induction generator sets can also be operated by the water needed for a fish-pass, or by water passing between two storage reservoirs at different levels.

The induction generator is basically a squirrel-cage induction motor driven at above synchronous speed by an ungoverned turbine and, when switched into a transmission system to which is connected synchronous plant, it supplies a fixed load settled only by the degree of opening of the turbine control gate and by the water head available. The magnetising current is drawn as a reactive load from the system and the voltage and frequency are those

years, and even installations involving synchronous plant of the order of a hundred megawatts can find place for asynchronous generators rated at anything from 20 kW to 5,000 kW. These machines can develop useful power from any compensation water which may have to be let down past the dam to flow in the old river bed, from which the main flow has been diverted in order to feed the power station. If the station is situated a long way downstream a considerable stretch

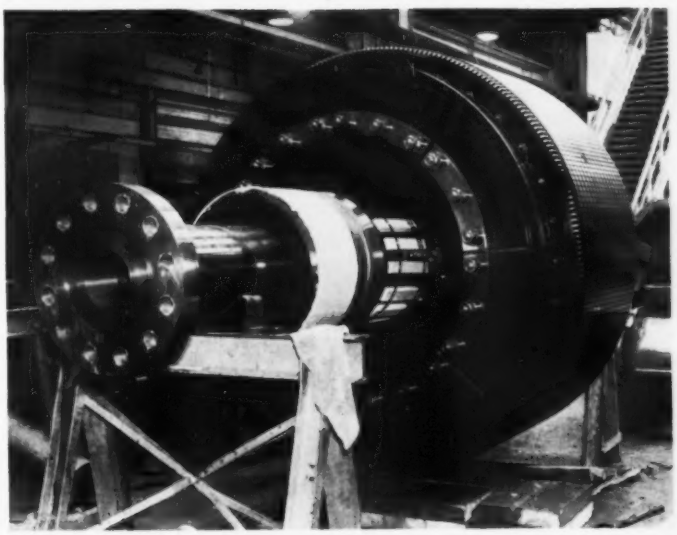


Fig. 30.—Rotor for induction generator (Bruce Peebles)

of the system. Thus no voltage regulator or excitation equipment is needed. The resulting unit can therefore be exceedingly simple and may be some 30 per cent. less in cost than a normal governed turbine with synchronous alternator.

The mechanical design of the induction generator has raised new problems which have been solved successfully. For instance, the rotating parts must be able to withstand running at the runaway speed of the turbine for prolonged periods since the station is very often unattended and loss of the load introduces this condition unless automatic devices are included to close the intake gate, and these are only justified on the larger machines.

A great variety of these machines has been installed in Scotland since the war, including some with vertical shafts, and photographs of the stator and rotor for such a machine rated at 4,000 kW, 336 r.p.m. are reproduced in Figs. 29 and 30. Reference has already been made in an earlier section to the 5,000 kW, 300 r.p.m. (synchronous) horizontal induction generator at the Sron Mor station in Scotland.

Voltage Regulators

Just as the electrical design of water-wheel alternators has kept pace with the increasing demands imposed by long and extensively interconnected transmission systems, so the voltage regulators for these machines have been called upon to meet the problems of voltage control and system stability which arise.

'Indirect' voltage control where the measured alternator voltage is applied to a mechanical relay which in turn varies the resistance in the excitation circuit cannot be sufficiently quick acting to deal effectively with the transients in a long transmission system, and the 'direct' type of voltage regulator has been developed for this condition. In this type the measured alternator voltage (plus any other quantities such as alternator current for line drop compensation) is rectified and applied to an electrical network where it is compared with a standard voltage. The out-of-balance is amplified in a variety of ways. The amplifiers incorporate either magnetic amplifiers or transistors with or without a rotating stage, and the resulting signal is applied to additional fields on the main exciter. In this way the speed at which the disturbance in the alternator voltage is felt by the exciter is limited only by the time constant of the excitation circuit. To reduce this time constant and so take the fullest advantage of a direct voltage regulator, exciters with laminated pole frames have been used for several large water-wheel alternators.

The very high speed response of these new regulators makes it possible for the maximum use to be made of the capability of the alternator, particularly when operating on leading power-factors.

Because of the ease with which electrical circuits can be re-arranged it is possible to allow for various operating conditions (which can be selected at will) in the one regulator. There is no virtue in endeavouring to keep constant terminal voltage on a machine feeding into a network which is large relative to itself, and under this condition constant power-factor control is adopted but with reversion to constant voltage if the machine becomes isolated from the system. A third method is called for when the alternator runs as a synchronous condenser and then constant MVA output is required. All three of the above conditions can be and have been met by the one regulator.

Testing

The alternator designer would naturally wish each of his machines to undergo a full range of running tests in the works to prove the correctness of any assumptions he has made in the design stage, particularly when he is reaching into new fields. British manufacturers are well equipped with testing apparatus in their works and also with the necessary space and cranage to enable testing to be done, even on the largest sizes of machine. However, unlike a steam-driven turbo-generator the large water-wheel driven alternator has to be sub-divided to a very extensive degree for transport, involving the splitting of the stator winding and the breaking down of the laminated rotor rim. Further, from a mechanical point of view it is not possible to reproduce in the works an arrangement of the foundations for a vertical machine comparable with that which will exist at site. This can also apply to the ventilation circuit.

The time and expense involved in carrying out full assembly followed by dismantling of these

large machines are in themselves often sufficient for the customer to rule out running tests in the works. Considerable advances have been made in the technique of carrying out full performance tests on an alternator at site, and one of the two 85 MVA 85·7 r.p.m. alternators supplied from Britain to the United States was tested in this way. The tests included running the alternator as a motor with the turbine runner uncoupled in order to determine the division of windage and friction losses between the turbine and alternator. As a result of these tests it was found that an adjustment of the formula used in the United States for this division is necessary for large machines.

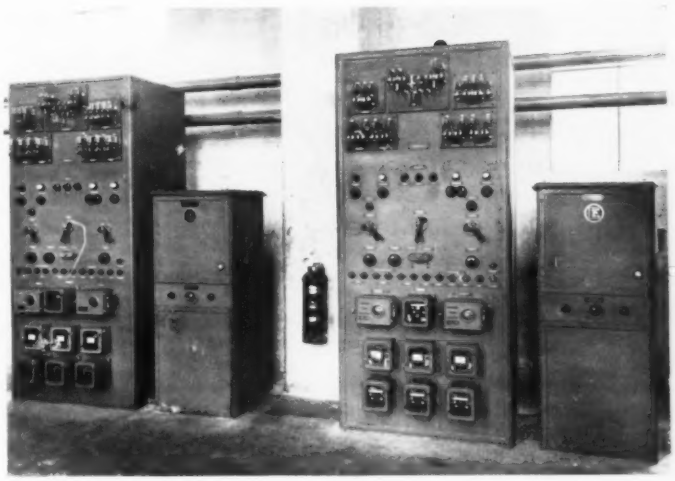


Fig. 31.—*Automatic control panels supplied for Earlstoun in* 1936 (*English Electric*)

POWER STATION AUXILIARIES

Auxiliary Motors and Switchgear

The amount of auxiliary electrical equipment required for even the largest hydro-electric installation is extremely small by any standard and especially so in comparison with a thermal station. The largest single motor for driving an auxiliary is almost invariably the governor-oil-pump motor which will have a rating in the range from 3 to 100 h.p. according to the size and type of turbine. In some stations fairly large draft-tube dewatering-pump motors and/or blower motors for synchronous-condenser operation are installed. Apart from these and motors on the service cranes in the station and on the civil works the unit auxiliary motors are small in size and few in number. Furthermore the mechanical design of the plant is such that it can continue operating for a short time, or sometimes for a prolonged time, without any external auxiliary supply. This all results in the auxiliary switchgear being simple and it is possible to mount the distribution and motor-control gear for each unit on a single board. The auxiliary voltage is the standard L.V.A.C. supply of the country, 415 or 230 volts as the case may be, and direct-on-line squirrel-cage motors are used except in a few cases.

Instrument and Control Panels

In pre-war years the turbine had associated with it a simple gauge-board carrying a few pressure gauges, and other instruments and control were scattered around the station. With the advent of the hydro-electric station as a major generating unit in an important system, greater emphasis came to be placed on reliability of generation and ease of control, resulting in a centralising of the instruments, and control and protective facilities.

Remote or automatic control of hydro-electric stations is no new thing and stations of this type have been generating since before the war : the increase in the number of stations in an area, coupled with the difficulty of persuading sufficient numbers of suitable operating staff to live in remote areas, has sustained the demand for such stations. British industry has been in the forefront of the development of the necessary electrical schemes for installation not only in Scotland where many of the stations are arranged for unattended operation but also in New Zealand, Australia, Rhodesia, and Spain. A comparison between the appearances of pre-war and recent control equipment is shown in Figs. 31 and 32.

The control board shown in Fig. 32 contains complete control and protective equipment not

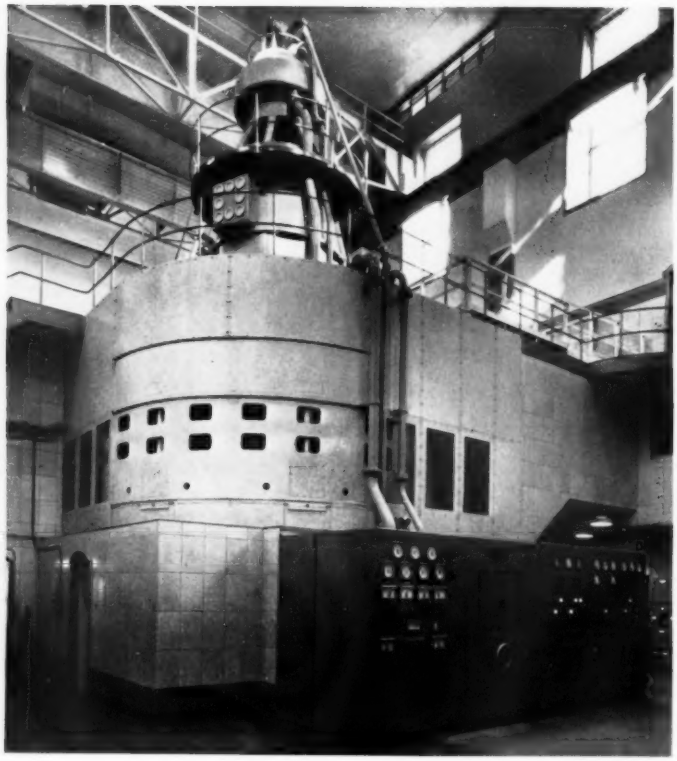


Fig. 32.—Automatic control panel and governor cabinet supplied for Invergarry in 1955 (English Electric)

only for the turbine and alternator but also for the transformer and main switchgear. In addition the voltage regulator is included in the board.

TRANSPORT AND ERECTION

Transport

No article of this nature on hydro-electric work would be complete without reference to the problems of transport and erection of the equipment which are associated with it.

The maximum weights to be dealt with can normally be kept within reasonable limits by subdivision of components, and it is therefore the main transformers, also required for any scheme, which decide the weight-carrying capacity of the transport vehicles and of the roads and bridges leading to the site. There are nevertheless some very heavy parts to be dealt with and even the shaft for the British-made alternators for McNary power station in the United States constituted a record transport achievement for the Pennsylvania Railroad.

The physical bulk of the water-turbine and alternator parts is however a major problem, aggravated, as is so often the case, by the remote location of the site. All is well when this problem is reviewed in sufficient time jointly by the customer, the manufacturer, and the transport authorities concerned, and if the power station is underground this is especially necessary in order to keep subdivision of components to a minimum. Thanks to such collaboration it was possible for the spiral casing, the inlet valve, and the alternator rotor for the 17 MW sets in the underground Ceannacroc and Glenmoriston power stations in Scotland each to be delivered as a complete item, thus saving assembly time in a cramped turbine room and resulting in a more satisfactory operation from all points of view. Fig. 33 shows the spiral casing entering Ceannacroc power station.

In other places it has been necessary for the plant manufacturer to purchase special transporter vehicles the cost of which must eventually find its way back to the plant purchaser. The disadvantage of such an arrangement is that the manufacturer cannot normally be expected to know the ultimate needs of the purchaser for such a vehicle and to what other purposes he intends to put it.

Erection

Site erection of large hydro-electric plant involves an appreciable number of operations more usually considered as works responsibility, including the welding up of heavy plate sections,

the building up of laminated rotor rims or the shrinking on to the shaft of heavy rotor plates, and the jointing or even complete winding of alternator stators.

All these operations involve the provision in the power station of space and lifting facilities which may never again be used to the full. There is an understandable tendency on the part of the civil designer to restrict these facilities, sometimes to an impossible degree. Restrictions there must be, due to the short time some of the facilities are used, but these have to be weighed against the increased time which will be taken on plant erection with possible loss of revenue, and against the subsequent inconvenience of carrying out a major overhaul of one machine while efficient operation of the rest of the station continues.

Fig. 33.—*Spiral casing entering Ceannacroc power station* (*English Electric*)

Collaboration between purchaser, civil engineers, and plant manufacturers is also essential for the construction stage of any project. This collaboration starts with the planning of the access roads, bridges, and even special docks which may be necessary. The civil contractor also normally provides all the housing for the plant erection staff as well as for his own staff, and the isolated nature of some sites has meant that the camp has had to be fully self-supporting. This is an important consideration in these days of shortage of skilled personnel if the right type of people is to be kept on outside erection work.

Although assembly of the rotating parts of the turbine and the complete alternator erection can and should normally take place after the civil works in the area have been completed, there are substantial parts of the turbine to be embedded in the concrete and even supporting the concrete. The spiral casing is a typical example. The increase in size of casings has made it necessary to split them sometimes into many components, but welding at site is now well established and so there is no difficulty provided that the proper supports and lifting tackle are available. The placing of the concrete in relation to the spiral casing erection is one of the typical operations where proper collaboration in drawing up the timetable and planning the arrangements can produce overall economy and result in earlier production of power.

PROSPECTS FOR THE FUTURE

Future Development Along Conventional Lines

Sufficient has been said under the heading 'World Power Requirements' (in Part I) to show that a great part of the world's potential water power still remains to be developed, and that the demand for electrical energy, both in the highly developed countries and in those not so highly developed, is increasing rapidly. It has been shown that during the forty years in which the larger water turbines have been manufactured in Britain British engineers have been closely associated with almost

every major advance in design and constructional techniques. While there has been no corresponding fundamental change in alternator design, so that neither Britain nor any other country can claim to have led the way, British electrical engineers have successfully taken part in solving all those problems introduced by the really spectacular increases in output and physical dimensions and by the adoption of new methods of mechanical construction.

At the present time therefore it is true to say that British Industry is able to supply and to put into operation any type and size of hydro-electric plant which purchasers anywhere in the world are likely to require. British consulting engineers are equipped to carry out any investigations into proposed schemes and to undertake any other tasks that may be required of them in connection with hydro-electric projects.

The development of water power since 1945 has been on a scale far greater than anything which preceded it. Fears have been expressed that the more easily and economically developed projects are becoming exhausted, with the result that there may be in the near future a slackening off in the exploitation of this form of power. The authors are confident that for a good many years to come the development of water power will hold its own *vis-a-vis* the development of other sources of power. There are several reasons for this confidence.

The constant pressure of world energy demand on the available resources, and the improving standard of living in many of the more advanced countries has caused, and may continue to cause, a spectacular rise in the prices of coal and oil, and so is causing an increase in the cost of electrical energy generated from these fuels. This is tending to raise the economic limit to the exploitation of water power and to bring it continually closer to the physical limit.

The intense demand for the fossil fuels imposes a heavy burden on the balance of payments of countries which are developing. Much of this demand is an unavoidable consequence of their industrial development. For instance, motor spirit and fuel oil used in industrial processes have to be imported. Such countries will therefore wish to avoid the importation of further fuels for the purpose of generating electricity and will want to make as much use as possible of their native water power in order to ease the balance-of-payments burden. In pursuit of this aim they will probably consider it well worth while to instal hydro-electric plant even when the cost of the power thus produced is greater than it would be from an equivalent thermal plant.

Many developing countries have to proceed with schemes for irrigation, navigation, flood control, and water conservation for domestic or industrial use, and this means the building of dams and the carrying out of other civil-engineering works. In many cases the conditions would be suitable for the installation of hydro-electric generating machinery at comparatively little additional expense. Where the immense benefits to be derived from flood control and irrigation enable a portion of the capital cost to be rightly allocated to them, an associated hydro-electric power scheme, which could not otherwise be contemplated, may become economic.

The Impact of Nuclear Power

When the commercial operation of nuclear-power plants first became a possibility, fears were expressed in some quarters that the death-knell of hydro-electric plants was sounding. More careful and detailed consideration of all the problems has brought about a calmer outlook, and many engineers today are aware that, of all the alternative ways of producing electrical energy, water power is the one most suited and necessary to run in harness with, and act as complementary to, nuclear power. Nuclear reactors are, of course, in their infancy, and the next few years will undoubtedly bring about many changes and improvements, as experience is gained in design, construction, and operation. At present, however, the economics of nuclear power generation suggest that the reactor and its associated generating machinery work at a steady load, as base-load plant.

Water-turbine generating plant has for long been operated as the ideal peak-load plant, although in certain circumstances it is also eminently suitable for use as base-load plant. The rapidity with which a water-turbine set can be started up from rest and loaded up to its full capacity makes it particularly suitable to be used as peak-load plant, and the ease with which it can be regulated enables it to take all

the load variations, while the thermo-nuclear plant is steadily meeting the base-load.

Indeed, exciting prospects are opening up for hydro-electric schemes involving pumped storage to be installed in locations where the natural rainfall is far too little to justify the installation of straight water-driven generating plant. In this way, the coming of nuclear power, far from rendering hydro-electric power unnecessary and out of date, promises to act as a stimulus for the production on a large scale of hydro-electric plants of the pumped-storage type, which would not have been contemplated without it. In view of the importance of pumped storage in the immediate future, a special section of this article has been devoted to it, with particular reference to the hydraulic machines utilised.

It is envisaged that large pumped-storage schemes, similar to the Blaenau Ffestiniog scheme, will be economically advisable in many parts of the world to supplement not only base-load nuclear generating plant but also large thermal plants working on the more conventional fossil fuels. If no attempt is made to combine the pumped-storage with straightforward generation from available water power, there is a much greater degree of freedom in the choice of suitable sites, and the cost of the associated civil engineering may be greatly reduced. Where a country has a mountainous, or even a hilly, seaboard, it may be possible to create an upper reservoir at comparatively low expense quite close to the sea, and to use the sea itself as the lower reservoir. Several such schemes are at present under consideration in Britain. It may indeed turn out that modern developments in pumped-storage technique will enable more serious attention to be given in the future to the development of tidal power, one of the serious disadvantages of which is the cyclic progression through the twenty-four hours of the periods when the maximum power is available.

Summary

This review of some of the most important factors indicates that hydro-electricity has still a very important contribution to make towards filling the almost exorbitant demands of the peoples of the world for more and more power. Many natural sources of water power remain to be exploited, and it is becoming increasingly practicable and increasingly economic to develop those situated in places more remote from centres of load ; the power of the tides has hardly been harnessed at all as yet, and there is great scope for the installation of pumped storage machinery to supplement and make more economic the use of generating machinery of different types including that water-driven.

Very few of the developments foreseen will be in Britain, but it is incumbent on the section of British Industry concerned with the manufacture of hydro-electric plant to maintain the efficiency which it has built up, and to keep itself in the forefront of progress, so as to ensure that it continues to contribute an important quota to developments proceeding throughout the world.

ACKNOWLEDGEMENTS

The authors are grateful to those authorities referred to in the article from whom they have taken statistical and other data, and also to the following manufacturing companies which have generously supplied details, photographs, and drawings of their turbines and alternators :—

The Armfield Hydraulic Engineering Co. Ltd.
Boving and Co. Ltd.
The British Thomson-Houston Co. Ltd.
Bruce Peebles & Co. Ltd.
The English Electric Co. Ltd.
The General Electric Co. Ltd.
Gilbert Gilkes and Gordon Ltd.
The Harland Engineering Co. Ltd.
Metropolitan-Vickers Electrical Co. Ltd.

APPENDIX I

The great variety of designs of hydro-electric sets to suit the individual conditions stipulated makes it impossible to give in an article of this nature anything like a comprehensive treatment of the types which are available. A small selection has however been made in this appendix covering each main type of turbine and alternator.

The sets illustrated are :—

1. 2·4 MW Kaplan turbine and induction generator by The Harland Engineering Company.
2. 30 MW horizontal impulse turbine and alternator by Boving & Company and The British Thomson-Houston Company.
3. 59 MW horizontal alternator by The General Electric Company.
4. 91 MW Kaplan turbine and umbrella alternator by The English Electric Company.
5. 114 MW vertical Francis turbine and two-bracket alternator by The English Electric Company and Metropolitan-Vickers Electrical Company.

A wider selection of turbine and alternator cross-sectional drawings has been added in Appendix II.

1. 2.4 MW Kaplan Turbine and Induction Generator *by The Harland Engineering Company*

Fig. 34 shows the cross-sectional arrangement of the machine supplied by The Harland Engineering Company to the Achanalt power station of the North of Scotland Hydro-Electric Board. This set is of a relatively small output but contains several interesting features. The Kaplan turbine is of 3,420 h.p. rating and operates under a designed net head of 46 feet, running at a normal speed of 336 r.p.m. on full load.

No speed-sensitive governor is required for the turbine since the set will run at the speed determined by the load and the electrical system frequency. The amount of load on the machine is determined by the amount of turbine-gate opening which can be varied either according to the water level at the intake or by manual control. The operation of the turbine gates is by an oil-pressure-operated servomotor.

The turbine guide bearing and also the two induction generator guide bearings are of the pivoted-pad self-lubricating type, and in the case of the generator bearings water cooling is provided.

The vertical induction generator has a rating of 2,400 kW at 11 kV and is of the open ventilated two-bracket type.

The rotor is of the segmental squirrel-cage type and carries a flywheel at each end to provide hydraulic stability under turbine runaway conditions when the speed can rise to 865 r.p.m. The usual rotor braking and jacking system is provided similar to that for a vertical synchronous machine.

No excitation system is required for the induction generator.

2. 30 MW Horizontal Impulse Turbine and Alternator *by Boving and Company and The British Thomson-Houston Company*

The Finlarig power station of the North of Scotland Hydro-Electric Board contains a single alternator supplied by The British Thomson-Houston Company, driven by an impulse turbine with inlet valves supplied by Boving and Company.

Fig. 35 shows the cross-sectional arrangement of the unit.

The turbine is of the 4-jet twin-overhung-runner type and is rated at 42,000 h.p., 1,250 feet net head (1,348 feet gross) which is the highest head in Scotland. The speed of the set is 375 r.p.m.

Each runner is fitted with 18 stainless-steel buckets which are bolted on to a forged-steel disc, and the nozzle and needle tips are also of stainless steel.

The two inlet valves are hydraulically operated and are of the rotary type, 36 inches diameter, and have a special rubber sealing device.

The alternator rotor is supported in two bearings with a turbine runner overhung from each end,

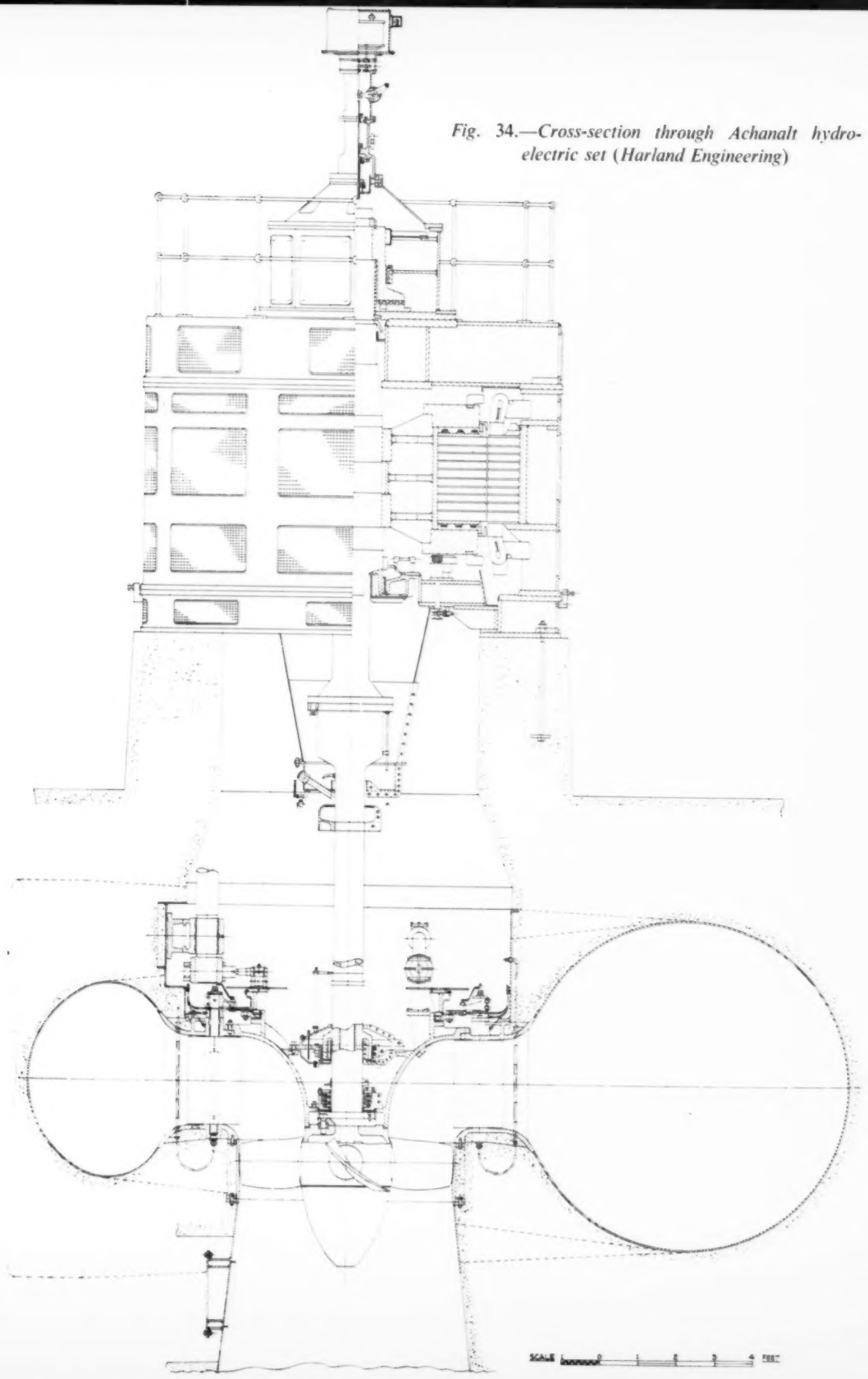


Fig. 34.—Cross-section through Achanalt hydro-electric set (Harland Engineering)

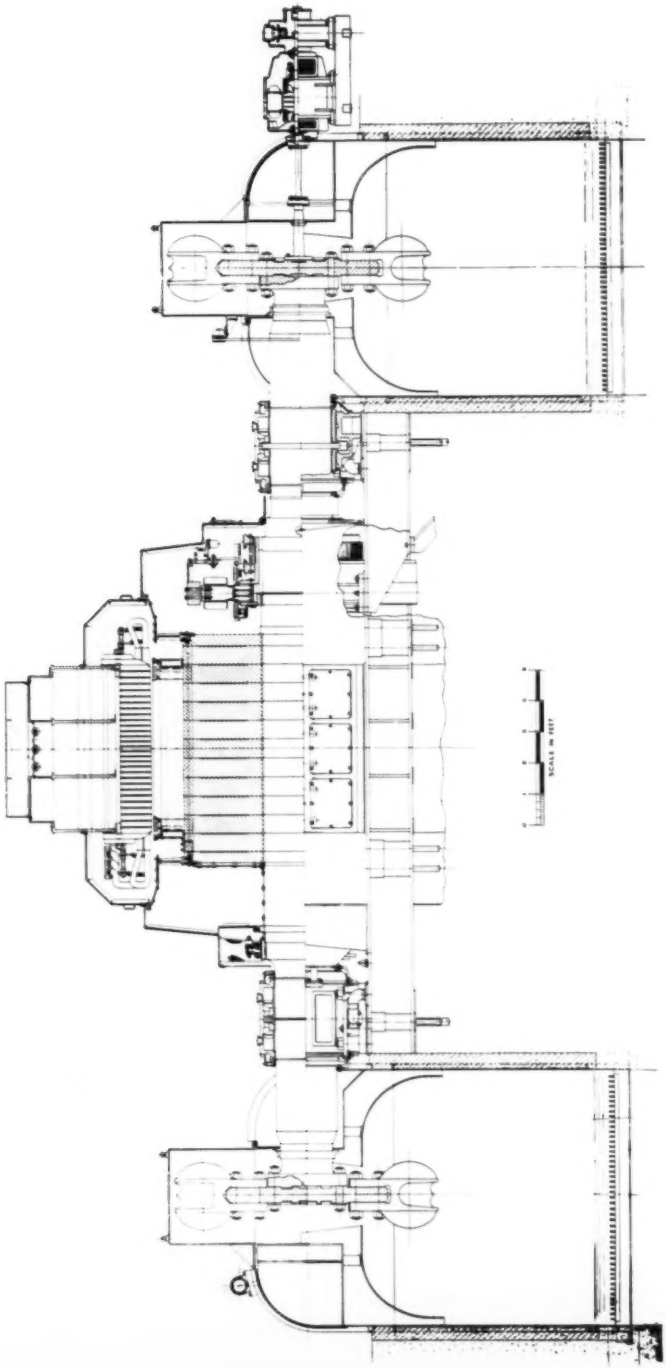


Fig. 35.—Cross-section through Finlarig hydro-electric set (Boving and British Thomson-Houston)

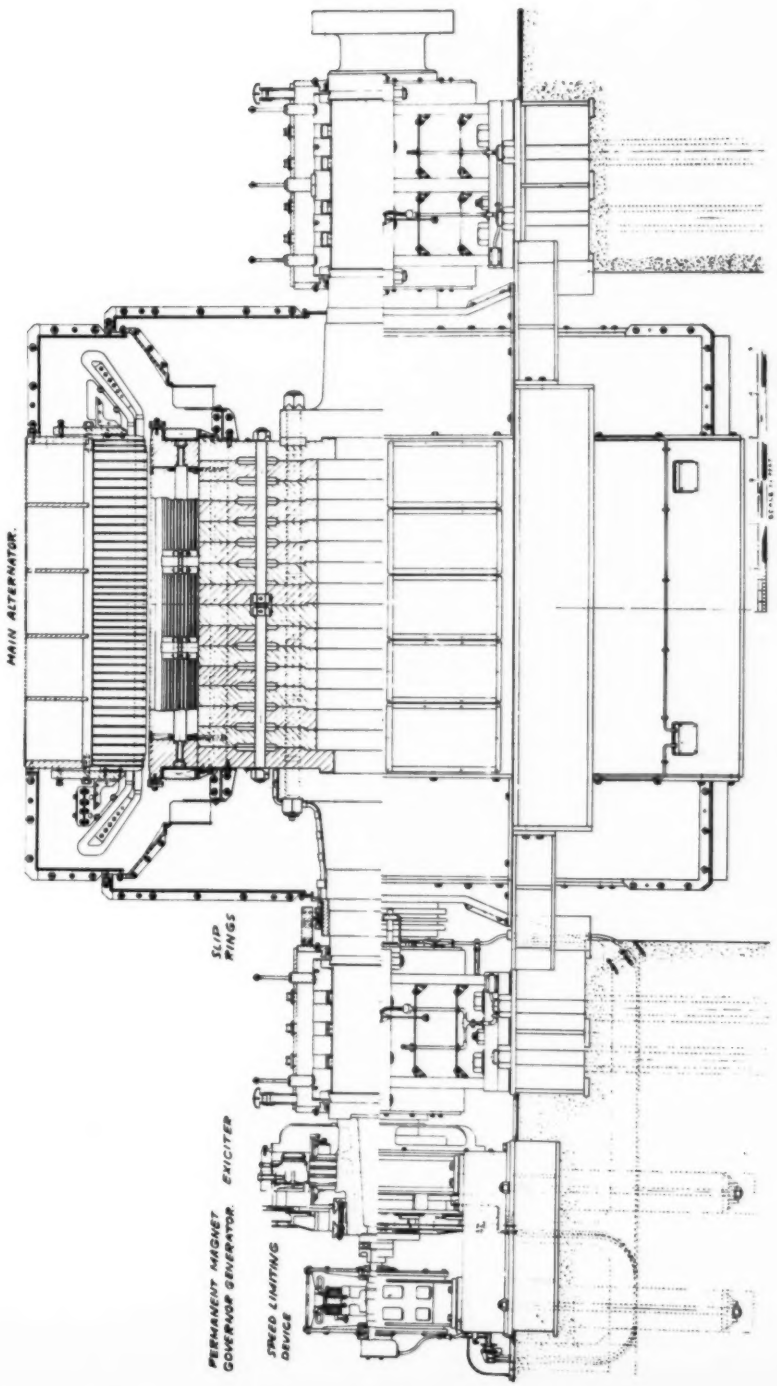


Fig. 36.—Cross-section through Aura alternator (General Electric)

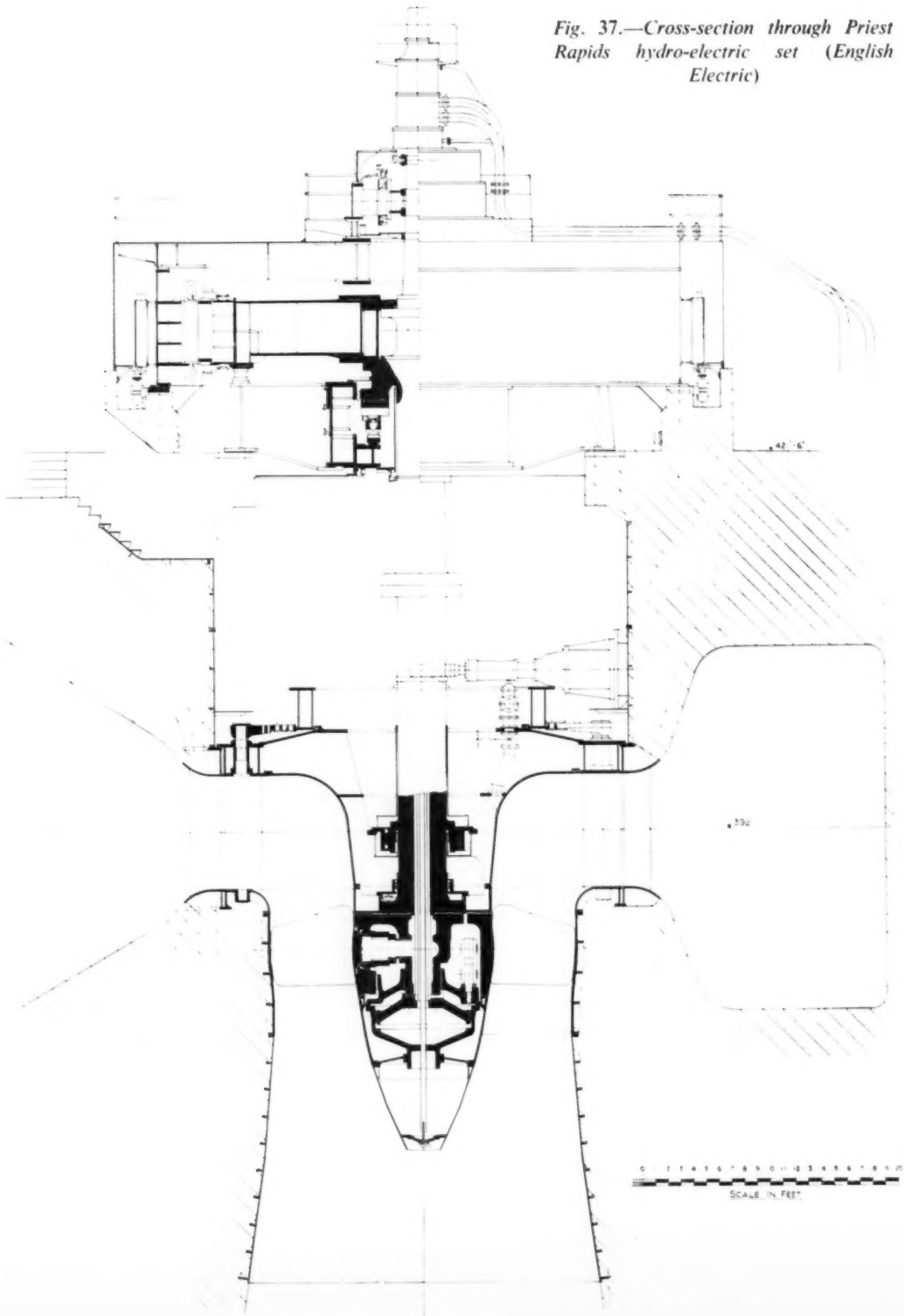


Fig. 37.—Cross-section through Priest Rapids hydro-electric set (English Electric)

and these are the only bearings for the complete set apart from those for the pilot exciter and governor alternator which are directly coupled at one end of the machine.

An interesting constructional feature is that the main exciter is located between the main bearings of the machine, its armature being carried on the main shaft. This reduces the overall length of the set.

The control equipment enables the set to be started up automatically by pressing a button either in the power station or in the control centre at Killin, some three miles away.

3. 59 MW Horizontal Alternator *by The General Electric Company*

Fig. 36 shows the cross-sectional arrangement of the horizontal-shaft impulse-turbine-driven alternator supplied by The General Electric Company to the Aura power station of Norges Vassdrags-og Elektrisitetsveson (Norwegian Watercourse and Electricity Board).

The alternator is rated at 62·5 MVA, 0·85/0·95 p.f., 12·3 kV and runs at 428 r.p.m. The mechanical design of the machine was largely dictated by the transport difficulties which imposed a weight limit of 60 tons.

The stator is built in two halves, and owing to the restricted head-room in the underground power station a special lifting beam had to be designed for use during erection on site.

The body of the rotor is made of steel plates bolted together in two groups to allow it to be shipped in two separate pieces, the poles with field coils having been previously removed as also the stub shafts. The steel plates forming the body of the rotor are secured to the flanges of the stub shafts by through-bolts of special construction.

The poles are secured to the rotor body by means of double-tee fixings and taper keys. A special detachable platform is provided to facilitate removal of a rotor pole and coil from the machine without lifting the top half of the stator.

The main exciter and permanent-magnet governor alternator are direct-coupled to the alternator.

4. 91 MW Kaplan Turbine and Umbrella Alternator *by The English Electric Company*

For the Priest Rapids power station of the Grant County P.U.D., United States, The English Electric Company is supplying ten turbines and alternators together with the associated step-up transformers.

Fig. 37 shows the cross-sectional arrangement of the generating unit.

The turbines which are of the Kaplan type operate over the wide head range from 33 to 84 feet and develop a maximum output of 131,000 h.p. under a head of 84 feet when operating at 85·7 r.p.m. The spiral casings are constructed in concrete with fabricated steel stay rings. The runners which have six blades are 23 feet 8 inches in diameter ; they are the largest so far built in Britain and are among the largest in the world.

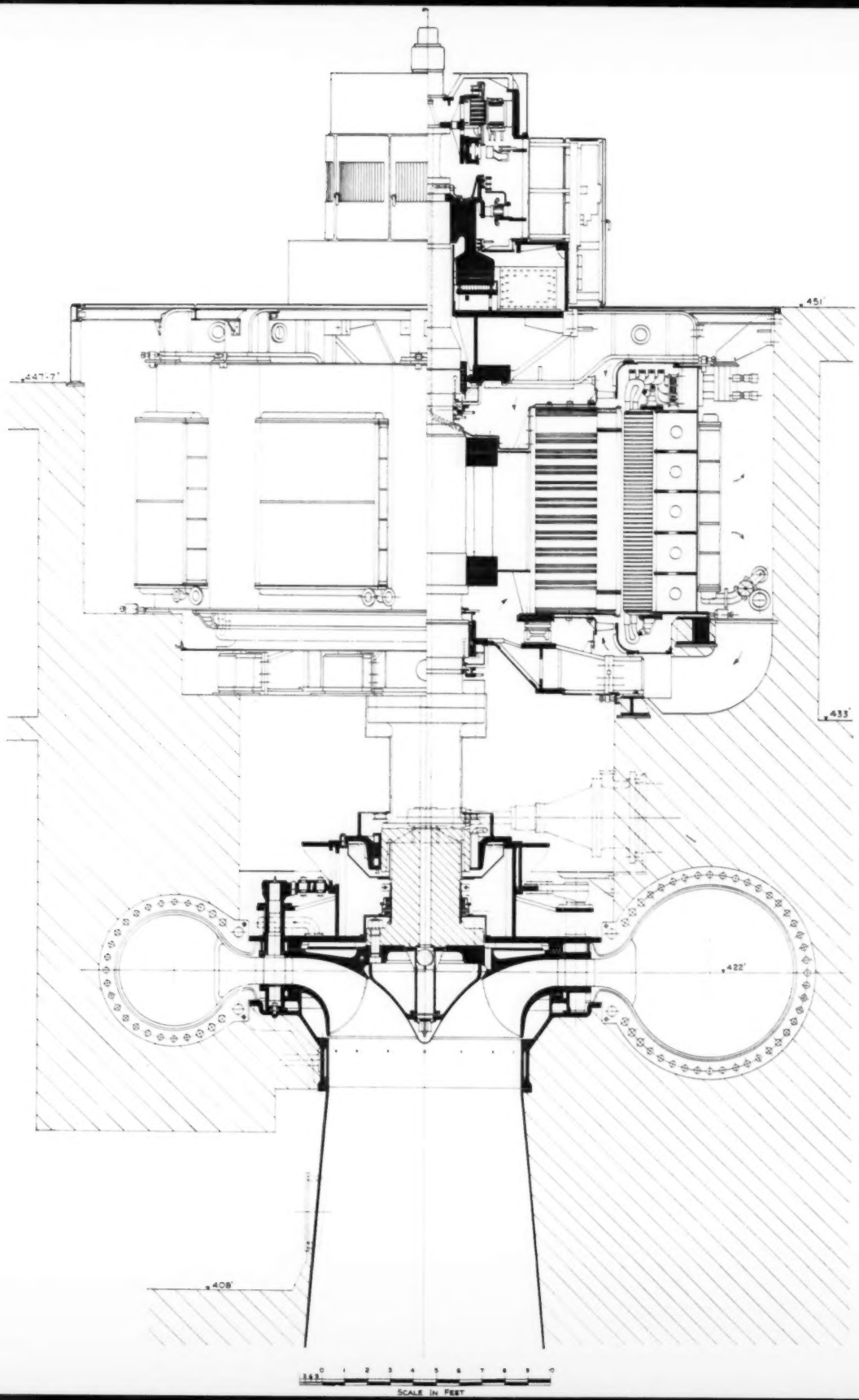
The runner-blade servomotor is oil-pressure operated and is located in the runner hub below the axis of the runner blades. Oil pressure from the pump set is supplied through tubes in the main shaft with an oil head at the top of the alternator.

The runner blades are steel castings with welded-on stainless-steel protection at the inlet and outlet edges and round the periphery.

Except for the runner and shaft almost the whole of the remainder of the turbine is of fabricated construction.

The turbine is solidly coupled to an umbrella-type alternator with a maximum output of 95,500 kVA at 13·8 kV. The complete rotor body is of fabricated construction with 14 arms bolted to the rotor hub. The rotor is designed to withstand a maximum runaway speed of 220 r.p.m.

The weight of the alternator rotating parts plus the weight of the turbine rotating parts and the hydraulic thrust, all of which amount to 1,600 tons, is taken by the thrust bearing mounted below the alternator rotor. The thrust collar has a loose face in accordance with American practice and the bearing is of the pivoted-pad type supported on an equalising ring. The whole bearing together with the alternator guide bearing, which is also of the pivoted-pad type, is immersed in an oil chamber which contains coils for cooling the oil and no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external lubricating system is provided. High-pressure oil jacking is included in the thrust bearing for use during starting and stopping of the machine.

The whole bearing assembly is supported by 10 fabricated bracket arms which also support the combined brake and jacking system for the rotor.

A self-excited exciter is mounted above the alternator rotor, and the armature is carried on a separate extension shaft.

There is no pilot exciter and voltage control is by means of a fully-static magnetic-amplifier-type regulator.

5. 114 MW Vertical Francis Turbine and Two-Bracket Alternator *by The English Electric Company and Metropolitan-Vickers Electrical Company*

The turbines and inlet valves for the first four units at Bersimis power station of the Quebec Hydro-Electric Commission were manufactured in Canada by the English Electric Company of Canada to designs supplied by The English Electric Company, Rugby, England, and the alternators which they drive were supplied by Metropolitan-Vickers Electrical Company. Fig. 38 shows the cross-sectional arrangement of the unit. The turbines are of the Francis type each rated at 175,000 h.p. under a head of 875 feet and run at 277 r.p.m.

The spiral casing which is 7 feet 9 inches bore at the inlet is of welded steel plate construction welded to a cast-steel stay ring. The maximum plate thickness is $2\frac{1}{4}$ inches and all the welds are fully radiographed.

The runner which weighs 21 tons is a single-piece stainless-steel casting 11 feet 11 inches diameter. Labyrinth sealing rings of stainless steel are fitted to the periphery of the runner, and the stationary sealing rings are of special bronze.

The guide vanes and the gate-apparatus lining rings are also of stainless steel.

The guide bearing is of the self-lubricating type with separate pads through which cooling water circulates.

Each turbine is fitted with a 7 feet 9 inches bore 'Straightflow' valve operated by pipeline water pressure and incorporating an isolating seal upstream of the service seal for maintenance purposes.

In addition to the spiral casing almost the whole of the turbine and valve is of welded steel plate construction.

The alternators, which are of the two-bracket type, are rated at 138,000 kVA at 0·95 p.f. 13·8 kV 60 cycles but they can be over-loaded to 150,000 kVA. When the machines were built, they were of the largest output in the 'free' world.

The rotor is of the laminated-rim construction and weighs with poles 320 tons excluding the thrust collar.

The thrust bearing is located above the upper guide bearing which is in the upper bracket and there is a second alternator guide bearing in the lower bracket below the rotor.

A permanent-magnet alternator rated at 37 kVA is mounted on the upper face of the thrust collar to provide a supply to the driving motor for the separately mounted buck-boost exciter. Above this alternator is connected the main exciter which is carried on a separate extension shaft.

The voltage regulator is of the static-amplifier type and works in conjunction with the buck-boost exciter set.

Fig. 38. (*Opposite*).—*Cross-section through Bersimis hydro-electric set* (*English Electric and Metropolitan Vickers*)

APPENDIX II

This appendix contains additional cross sectional drawings and brief descriptions of turbines and alternators which have been or are being supplied by The English Electric Company.

The sets illustrated are :—

1. 18 MW horizontal impulse turbine and alternator
2. 20 MW Kaplan turbine and two-bracket alternator
3. 30,000 h.p. vertical Francis turbine
4. 36·8 MW vertical Francis turbine and semi-umbrella alternator
5. 37·5 MW Kaplan turbine and semi-umbrella alternator
6. 62,000 h.p. vertical Francis turbine
7. 68,000 h.p. vertical Francis turbine
8. 75,000 h.p. vertical propeller turbine
9. 55 MW vertical Francis turbine and umbrella alternator
10. 80 MW two-bracket alternator
11. 110,500 h.p. vertical Francis turbine
12. 106 MW two-bracket alternator

1. 18 MW Horizontal Impulse Turbine and Alternator

The English Electric Company has supplied the four horizontal alternators and the impulse turbines which drive them in the Tully Falls underground power station of the Queensland State Electricity Commission.

Each set (Fig. 39) is of the 4-jet twin-overhung-runner type and is rated at 25,000 h.p. under a head of 1,439 feet when running at a speed of 600 r.p.m.

Each runner, which is a solid stainless-steel casting, has twenty-two buckets, and the nozzle mouthpieces and spear tips are also of stainless steel. The turbine incorporates the 'Seewer' diffuser system of regulation.

Two 28 inch bore 'Straightflow' valves are provided for each turbine. They are hydraulically operated using the pipeline water pressure and incorporate isolating seals upstream of the normal service seal for maintenance purposes.

The turbines and valves for the first two units were completely manufactured in Britain but for the second two units many items including the valves were manufactured in Australia.

The alternator which carries a turbine runner at each end of the shaft is of the two-pedestal-bearing type and is rated at 22,500 kVA, 0·8 p.f., 11 kV. The journal bearings are of the pivoted-pad type and no special arrangements were necessary to take axial thrust loading.

The machine has closed-circuit ventilation with the coolers located in a pit below the stator.

The rotor was despatched to site with the plates shrunk on the shaft but without the poles. The poles have extra thick end-plates with non-magnetic lips to give the required flywheel effect and are fixed to the rotor by double tee-heads.

An extension shaft passing through the casing of one of the turbines drives the exciter set through a flexible coupling. The main exciter is of the two-pedestal-bearing type and the governor alternator is overhung at one end. The pilot exciter is flexibly coupled to the main exciter and it also carries the overspeed device.

Two separate braking systems are provided to bring the set to rest. One is the standard hydraulic brake which operates by directing water on the back of the runner buckets, and to prevent reverse rotation a mechanical friction brake is also provided which bears on a special collar on the shaft.

Remote-control equipment is provided and the station has automatic synchronising.

2. 20 MW Kaplan Turbine and Two-bracket Alternator

The single hydro-electric set in the Invergarry power station of the North of Scotland Hydro-Electric Board is shown in Figs. 32 and 40.

The original proposal for Invergarry comprised two Francis turbines but these were eventually superseded by the single Kaplan turbine which was commissioned at the end of 1955.

The head varies from a minimum of 142 ft to a maximum of 181 ft and the turbine has a rated output of 28,000 h.p. under a head of 154·5 ft when running at 250 r.p.m. The turbine is one of the highest-head Kaplan turbines so far built.

The runner which has eight stainless-steel blades is 9 ft 5 in. diameter and rotates in a spherical runner envelope built up from stainless-steel plate. The powerful runner servomotor is located in the runner hub.

The turbine bearing is of the grease-lubricated type which runs in water. The main shaft gland of the multiple carbon-ring type is located above the bearing where it is accessible for inspection and maintenance.

The governor is housed in a cabinet which is part of the composite control board for the complete station.

The alternator is rated at 23,520 kVA, 0·85 p.f., 11 kV and is of the two-bracket type. The inlet air to the machine is drawn through louvres and filters from outside the station, and the outlet air is discharged direct into the station through the stator frame.

The rotor is of the solid plate type and the plates were shrunk on to the rotor at site. The main and pilot exciter armatures and the governor alternator rotor are carried on an extension shaft bolted to the top of the rotor shaft. The shafts are drilled throughout their length to accommodate the oil pressure pipe feeding the servomotor in the turbine runner hub.

A motor-operated jacking pump is provided to lift the rotating parts for examination of the thrust pads.

The set is arranged for push-button operation from a remote point at a later date.

3. 30,000 h.p. Vertical Francis Turbine

Three turbines have been supplied to the New Zealand State Electricity Board for their Atiamuri power station which is located on the Waikato River in the North Island. There is provision in the power station for a further unit if required.

The turbines (Fig. 41) which are of the vertical-shaft Francis type are rated at 30,000 h.p. under a head of 81 ft when running at 125 r.p.m.

While the greater part of the turbines was manufactured in Britain, the spiral casings and the draft tubes were fabricated in New Zealand.

The turbine runners, which are 13 ft 7 in. diameter, are of fabricated construction. They are built up from a cast-steel crown, a skirt built up from a steel casting and stainless-steel clad plate, and vanes pressed from stainless-steel clad plate. Thus the complete undersurface of the vanes and most of the runner skirt are protected by a layer of stainless steel.

The guide bearing is of the self-lubricating type with separate pads through which cooling water circulates. The shaft gland is of the multiple carbon-ring type.

4. 36·8 MW Vertical Francis Turbine and Semi-umbrella Alternator

Complete electrical and mechanical plant has been provided for the Hirfanli power station for the Ministry of Public Works, Turkey.

The power station contains three machines as shown in Fig. 42. The turbine is of the Francis type rated at 44,000 h.p. under a head of 197 ft and runs at 187·5 r.p.m. The spiral casing and speed ring which are of welded construction were completely fabricated in the works and despatched to site in quarters.

A 13 ft 7 in. butterfly valve similar to the 7 ft valve shown in Fig. 21 (Part I), except that the operating shaft is vertical and the servomotor is water pressure operated, is located at the inlet to each turbine. The 7 ft valve is used to isolate the compensation water discharge regulator.

The turbine runner is of fabricated construction built up from mild-steel parts with stainless-steel protection on the outside of the vanes.

The turbine guide bearing is of the self-lubricating type with separate pads through which cooling water circulates.

The alternator is rated at 46,000 kVA, 0·8 p.f., 11 kV and is of the semi-umbrella type in which a combined thrust and guide bearing is located below the rotor and a further pivoted-pad guide bearing is provided above the rotor.

The rotor is of the laminated-rim type carried on a fabricated hub which is bolted to the top

of the thrust collar. The poles, which are fixed to the rim by dovetails and taper side keys, carry coils which are fabricated from copper strip.

The lower bracket which carries the weight of the rotating parts and also the braking and jacking system is built up on a fabricated centre with six bolted-on fabricated arms.

The upper guide bearing is located on an extension shaft which also carries the governor alternator below the guide bearing and the sliprings above it. The top end of this extension shaft carries the shaft for the main and pilot exciters.

The alternator is closed-circuit ventilated and the coolers are bolted tangentially to the stator frame.

5. 37·5 MW Kaplan Turbine and Semi-umbrella Alternator

The English Electric Company has supplied the first two main units in the Hirakud No. 1 power station in the State of Orissa for the Government of India (Fig. 43).

Each turbine is of the Kaplan type and operates under a head which varies from 77 ft to 120 ft. The turbine is rated at 52,000 h.p. under a net head of 87 ft and runs at 150 r.p.m.

The runners which have six blades are 15 ft 9 in. diameter. The runner-blade servomotor which is located in the runner hub below the axis of the runner blades is oil-pressure operated, the oil pressure being supplied through tubes in the main shaft with an oil head at the top of the alternator.

The runner blades are stainless-steel castings and revolve in a spherical runner envelope built up from stainless-steel clad plate.

Except for the runner and shaft, almost the whole of the turbine is of fabricated construction. The spiral casing is of steel plate and was assembled to the speed ring in the works and then dismantled for despatch to site.

The turbine guide bearing is of the oil-lubricated sleeve type with external oil circulation and cooling.

The alternator is rated at 41,667 kVA, 0·9 p.f., 11 kV and is of the semi-umbrella type similar to the alternator previously described.

The rotor is of the laminated-rim type carried on ten short fabricated arms bolted to a composite cast and fabricated centre which is in turn bolted to the top of the thrust collar. The thrust bearing carries a total load of 975 tons and has an external oil circulating and cooling system. The lower bracket is built up of cast-steel arms bolted to a fabricated centre. The upper guide bearing is provided with oil from a separate pump.

The exciters and governor alternators which are carried on an extension shaft are cooled by air bypassed from the main alternator ventilation circuit.

One of the alternators was assembled in the works and a complete series of running tests was carried out including running at the full runaway speed of 273 r.p.m.

6. 62,000 h.p. Vertical Francis Turbine

Two turbines are being built to the order of the Rio de Janeiro Tramway Light and Power Company Limited for their Ponte Coberta power station in Brazil.

The turbines (Fig. 44) are of the Francis type each rated at 62,000 h.p. under a head of 115 ft. For the first years of operation the units will run at 115·4 r.p.m. and generate at 50 cycles but eventually the generators will be converted for 60 cycle operation when the speed will be 112·5 r.p.m.

The turbine runner which weighs about 41 tons is a single-piece steel casting 15 ft 10 in. diameter with stainless steel protection welded on to the vanes and skirt on the areas where cavitation might occur.

Most of the remainder of the turbine is of welded-steel-plate construction including the spiral casing which is 19 ft bore at the inlet with a maximum plate thickness of $\frac{7}{8}$ in. The dimensions of the spiral casing are such that it will be assembled in the works but will be shipped to site plate-small for final welding together.

The guide bearing is of the self-lubricating type with internal cooling of the pads, and the main shaft gland is of the multiple carbon-ring type.

7. 68,000 h.p. Vertical Francis Turbine

Four turbines are being supplied for the Table

Rock power station of the United States Army Corps of Engineers. The order for the first two units was obtained in 1954 and for the second two units in 1957.

The turbines (Fig. 45) are of the Francis type each rated at 68,000 h.p. under a head of 190 ft at a speed of 128·6 r.p.m. The rated output of 68,000 h.p. is at the point of best efficiency at 190 ft head, and the full load output at this head is 78,000 h.p. Provision is made for limiting the turbine output to 83,200 h.p. (the maximum generator capacity) at higher heads. An output of 43,000 h.p. is guaranteed at the minimum net head of 134 ft.

The spiral casing which is 16 ft 9 in. bore at the inlet is of combined riveted and welded construction. All joints made in the works are welded but all field joints are riveted in accordance with the requirements of the U.S. Army Corps of Engineers. Fig. 12 in Part I of this article shows the shop assembly of one of the spiral casings.

The turbine runner is a single-piece steel casting 14 ft diameter weighing about 35 tons. Areas of the vanes and skirt liable to cavitation are given welded-on stainless steel protection.

The shaft gland is of the carbon-ring type and the guide-vane seals incorporate rubber sealing rings of standard design. The turbine guide bearing is arranged with external oil circulation by electric-motor-driven pumps.

8. 75,000 h.p. Vertical Propeller Turbine

Sixteen vertical shaft propeller turbines (Fig. 46) are being supplied to the Hydro-Electric Power Commission of Ontario for installation in the Robert H. Saunders power station of the St. Lawrence Seaway Project. These represent the complete turbine installation on the Canadian side of the scheme and it is believed that this is the largest single order for water turbines ever placed with one manufacturer. The turbines were designed in Britain by The English Electric Company and are being manufactured in Canada by English Electric Canada, a Division of John Inglis Co. Limited. The first unit was commissioned on July 4th 1958 and further units are being completed at regular intervals.

The propeller turbines rated at 75,000 h.p. under 81 ft head run at 94·7 r.p.m. The runner is 21 ft diameter and as a result could not be cast or transported in one piece. Separate cast-steel vanes bolted to a cast-steel hub are therefore used.

The whole of the turbine except for the runner and shaft and a few minor items is fabricated by electric welding. The designs of the main cover with its separate outer ring carrying the upper guide-vane bearings, and of the regulating ring, were proved on models in The English Electric Company's mechanical research laboratory. The middle section of the main cover being separate, the runner can be removed without disturbing the gate apparatus.

A further ten turbines of identical design to those for the St. Lawrence Project are being supplied to the Beauharnois power station of the Quebec Hydro-Electric Commission where each unit will be rated at 73,700 h.p. under 78 ft net head at 94·7 r.p.m.

9. 55 MW Vertical Francis Turbine and Umbrella Alternator

Five water turbines and alternators are being supplied to the Rihand power station for the Uttah Pradesh Government, India. A cross-sectional arrangement of the unit is shown in Fig. 47.

Each turbine is of the Francis type and operates under a head varying from 143 ft to 250 ft. The rated output at 225 ft is 77,000 h.p. and the machine runs at 150 r.p.m. A steel-plate draft tube is provided which extends as a liner round the bend of the concrete tube. Each draft tube was completely built up in the works and then dismantled for despatch.

The spiral casing is of fabricated steel-plate construction, the plates being formed and assembled to the speed ring in the works and then dismantled for despatch to site. The speed ring is also of fabricated construction and is built up into four quarters which are bolted together.

The runner is 12 ft 11 in. diameter and is of cast steel. Parts of the vanes and the skirt are protected with welded-on stainless-steel deposit in the areas liable to cavitation.

No inlet valve is provided, protection of the set being by means of the intake gates in the dam.

The alternator is rated at 61 MVA, 0·9 p.f., 11 kV, and is of the umbrella type.

The laminated rotor rim is carried on fabricated box-section arms welded to a fabricated centre. The arms are divided at a bolted connection for transport.

The thrust bearing is carried in a fabricated assembly supported by box-section arms. The alternator shaft passes through the centre of the rotor and connects at its upper end to the extension shaft carrying the exciter and sliprings. The flexibly-coupled governor alternator is connected to the top end of the extension shaft.

The main exciter field is fed from a motor-driven control exciter which is itself controlled by a magnetic-amplifier type voltage regulator.

10. 80 MW Two-bracket Alternator

The McNary power station of the United States Army Corps of Engineers contains 14 generating sets and the last two alternators, shown in Fig. 48, have been supplied by The English Electric Company.

The alternator is of the two-bracket type and is rated at 73,684 KVA, 0·95 p.f., 13·8 kV, 85·7 r.p.m. with a continuous overload rating of 84,730 kVA.

The laminated rotor rim is carried on 14 fabricated arms which are bolted to a cast-steel centre shrunk on and keyed to the shaft. The poles are fixed to the periphery of the rim by dovetails.

The weight of the rotating parts and the hydraulic thrust totalling 1,740 tons is carried by the thrust bearing above the rotor. The bearing is of the pivoted-pad type and is contained in an oil chamber which includes coils for cooling the oil. High-pressure oil jacking is provided for the thrust bearing for the starting and stopping periods. The upper bracket supporting this bearing is shown in Fig. 27.

The pivoted-pad guide bearing is mounted separately from the thrust bearing above the rotor, and a further bearing is located below the rotor.

The voltage control is by means of a fully static magnetic-amplifier-type regulator.

A full series of efficiency and performance tests was carried out on the alternators at site, and included running with the turbine runner uncoupled to determine the friction and windage losses.

11. 110,500 h.p. Vertical Francis Turbine

The turbines and inlet valves for the four units in the Snowy T1 power station of the Snowy Mountains Hydro-Electric Authority, Australia, have recently been completed. The turbines (Fig. 49) are of the Francis type each rated at 110,500 h.p. under a head of 1,000 ft, but capable of developing a maximum output of 134,500 h.p. under the maximum net head of 1,095 ft. The speed is 375 r.p.m.

The spiral casing which is 6 ft bore at the inlet is of welded steel-plate construction welded to a cast-steel stay ring. The maximum plate thickness is $2\frac{1}{4}$ in. and in addition to having to withstand a test pressure of 900 lb/sq in. every weld is fully radiographed to ensure soundness. Fig. 14 in Part I of this article shows one of the completed spiral casings.

The runner which weighs 10 tons is 9 ft 3 in. diameter and is of fabricated construction. It is built up from a crown, skirt, and vanes, all stainless-steel castings, which are welded together, and after a heavy mild-steel crown is attached, stainless-steel labyrinth sealing rings are shrunk on. Fig. 16 (in Part I) shows one of the completed runners being dynamically balanced.

The guide vanes are stainless-steel castings and the gate-apparatus lining rings are of stainless-steel clad plate.

The guide bearing is of the self-lubricating type with separate pads through which cooling water circulates.

The turbine is arranged for downward dismantling of the runner through the draft tube. The upper parts of the turbine including the shaft bearing, regulating ring, and head cover are arranged for upwards and sideways dismantling without disturbing the alternator.

Each turbine is fitted with a 6 ft bore ' Straight-flow ' valve operated by pipeline water pressure and incorporating an isolating seal upstream of the service seal for maintenance purposes.

12. 106 MW Two-bracket Alternator

Fig. 50 shows the cross-sectional arrangement of the vertical impulse-turbine-driven alternator in the Kemano power station of the Aluminum Company of Canada.

The original order was for one machine rated at 106 MVA, 0·8 p.f., 13·8 kV, running at 327 r.p.m. with an overload rating of 122 MVA. A repeat order for a second alternator increased the rating to 114 MVA and the overload to 132 MVA which was achieved using the same alternator design.

The alternator rotor is built up of thick plates shrunk on to the shaft, and the poles are fixed to the rotor by twin tee-heads. The weight of the rotating parts is taken by a thrust bearing located above the rotor, which is supported by a cast-steel bracket with bolted-on cast-steel arms. There are two pivoted-pad guide bearings, one above and one below the rotor, with an external lubricating system.

The machine is housed in a square concrete pit with two air coolers in each corner for the closed-circuit ventilating system.

The power station is underground and feeds the aluminium plant at Kitimat.

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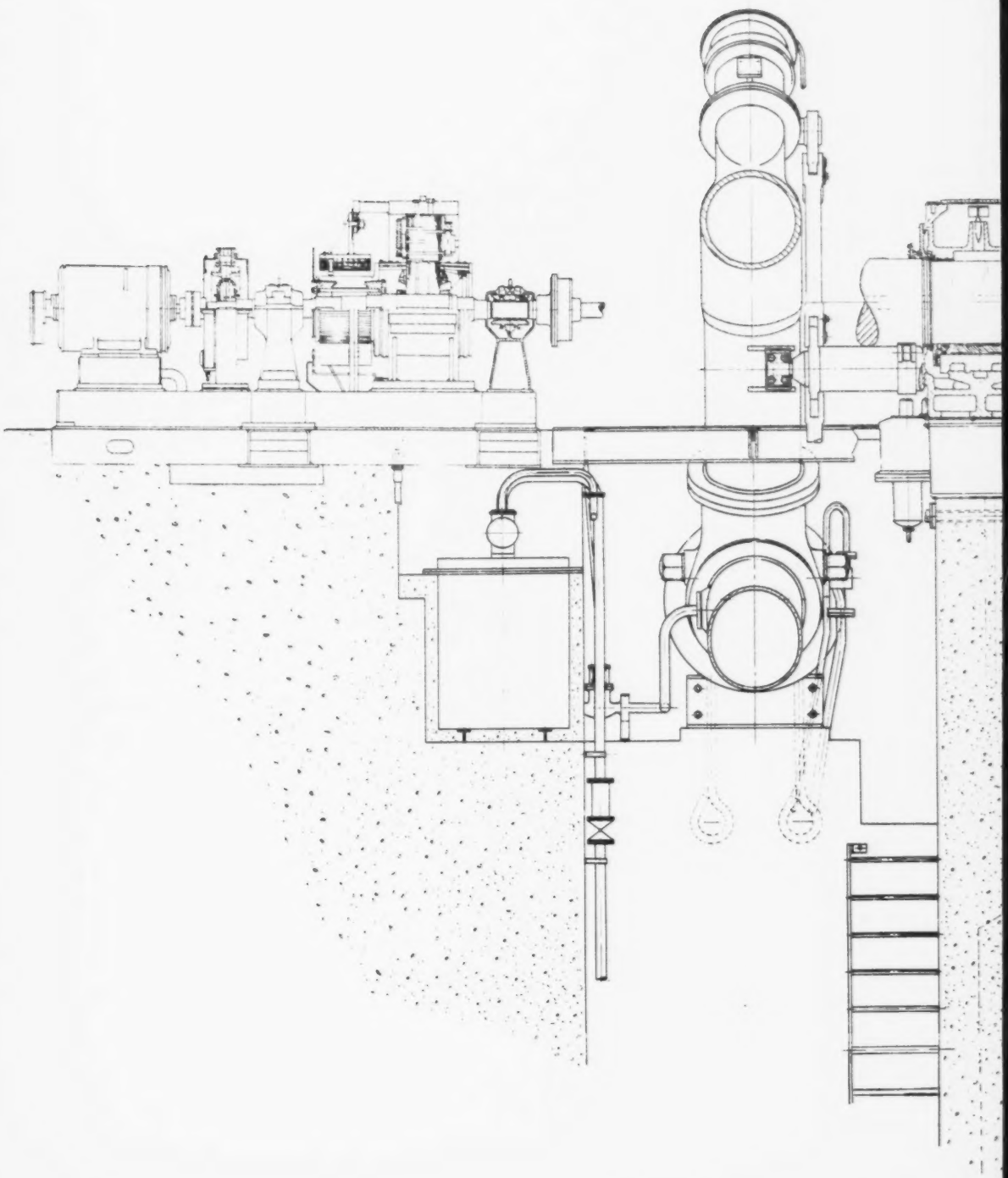

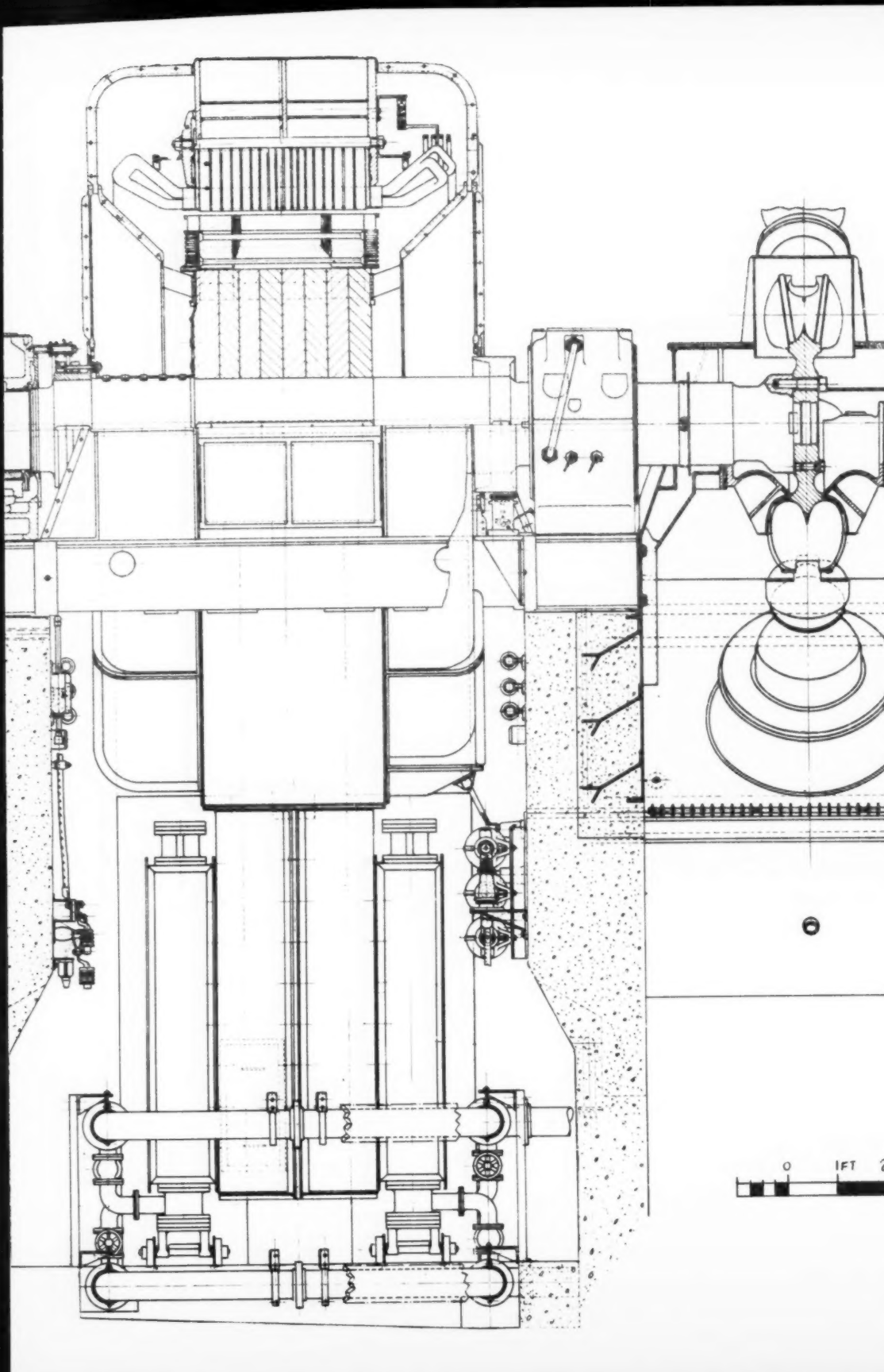
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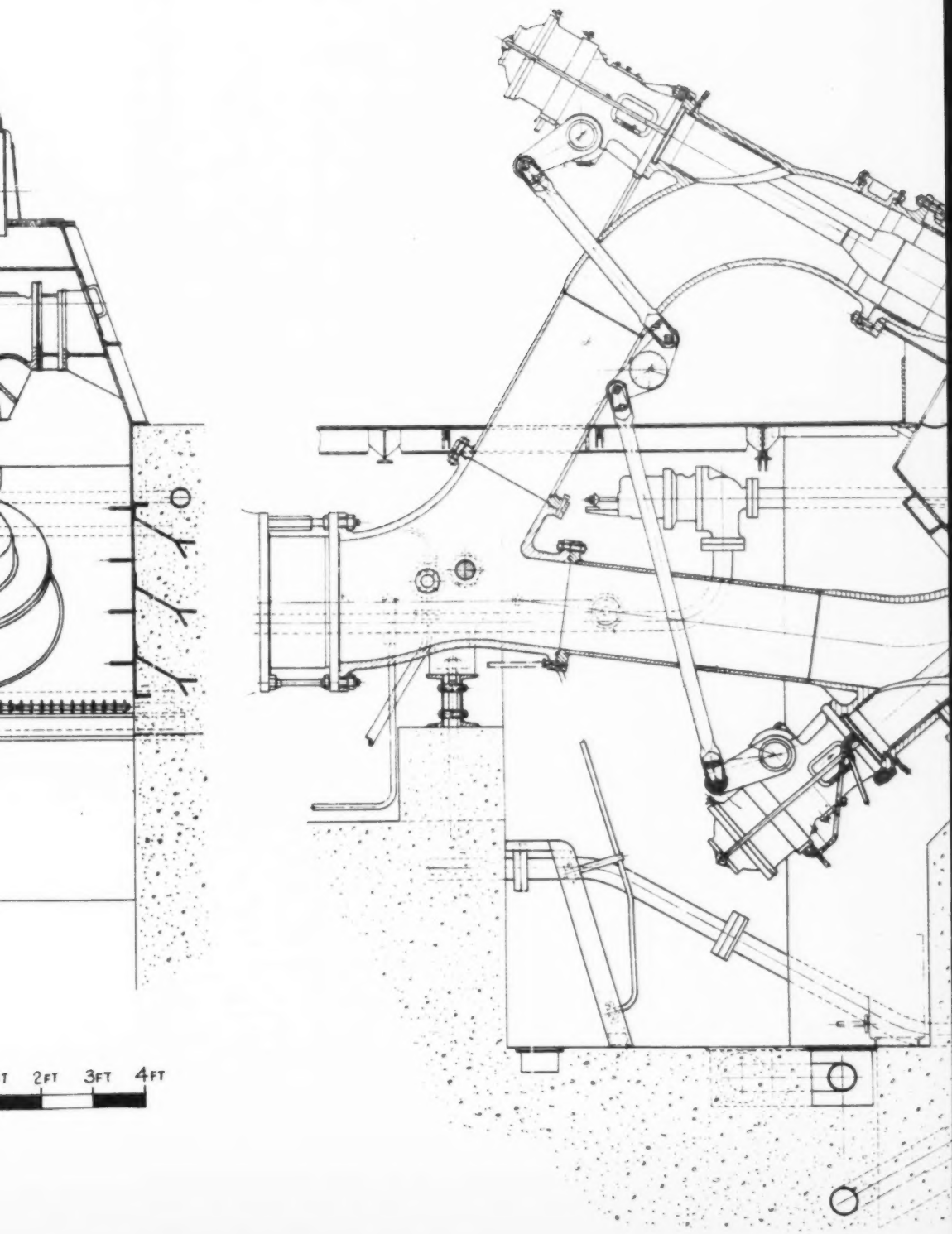
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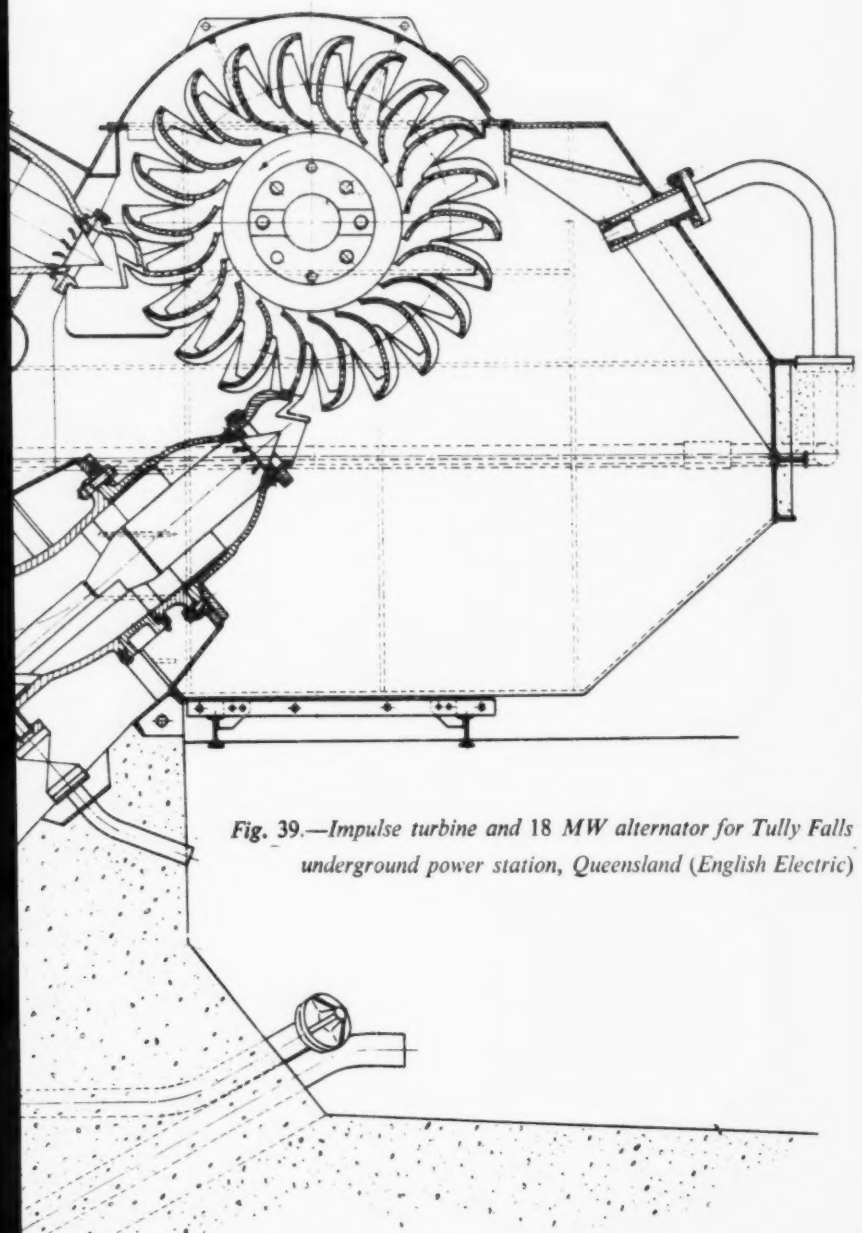
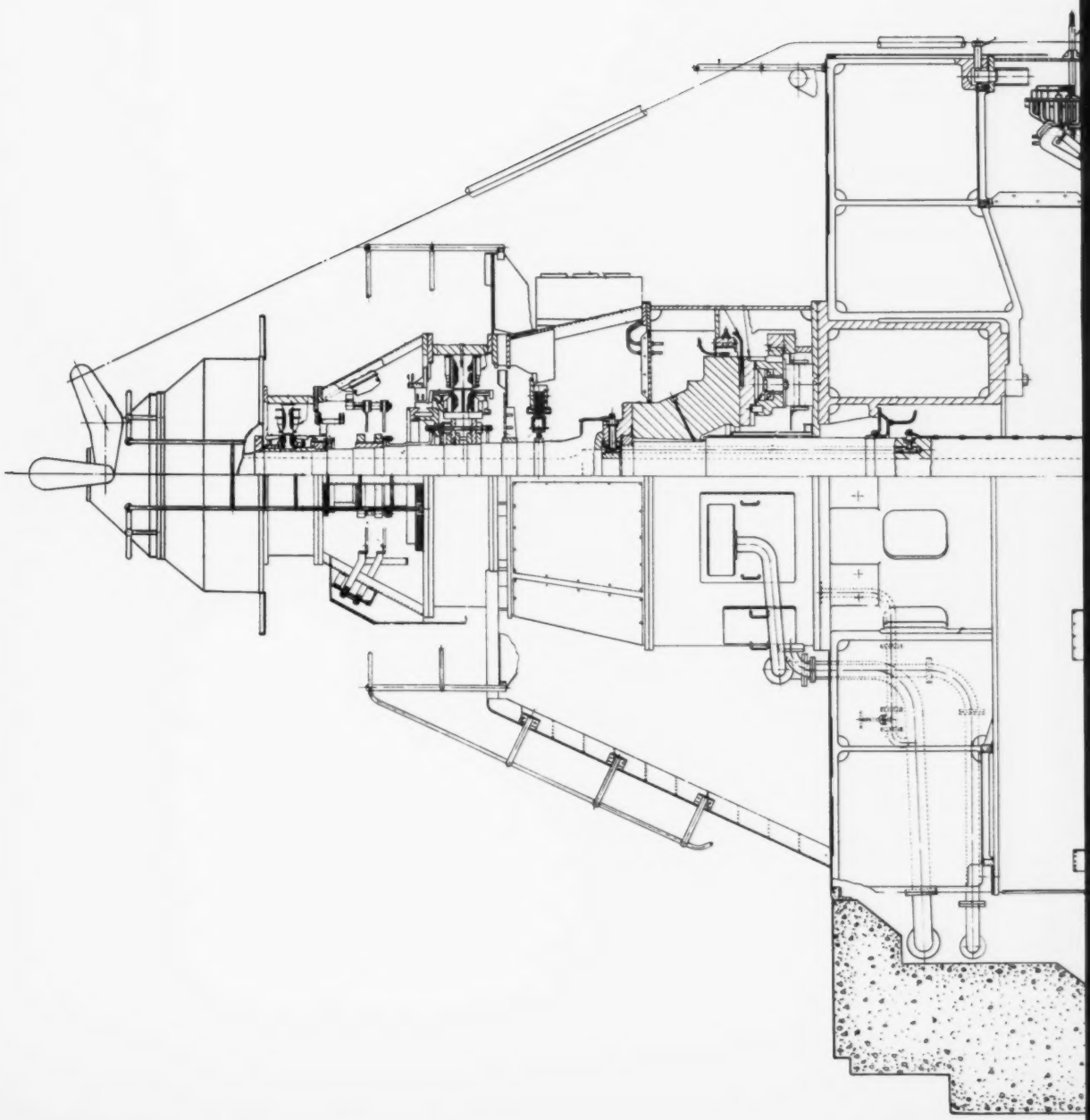


Fig. 39.—*Impulse turbine and* 18 *MW alternator for Tully Falls underground power station, Queensland* (*English Electric*)

Fig. 40.—Kaplan turbine and 20 MW two-bracket alterna



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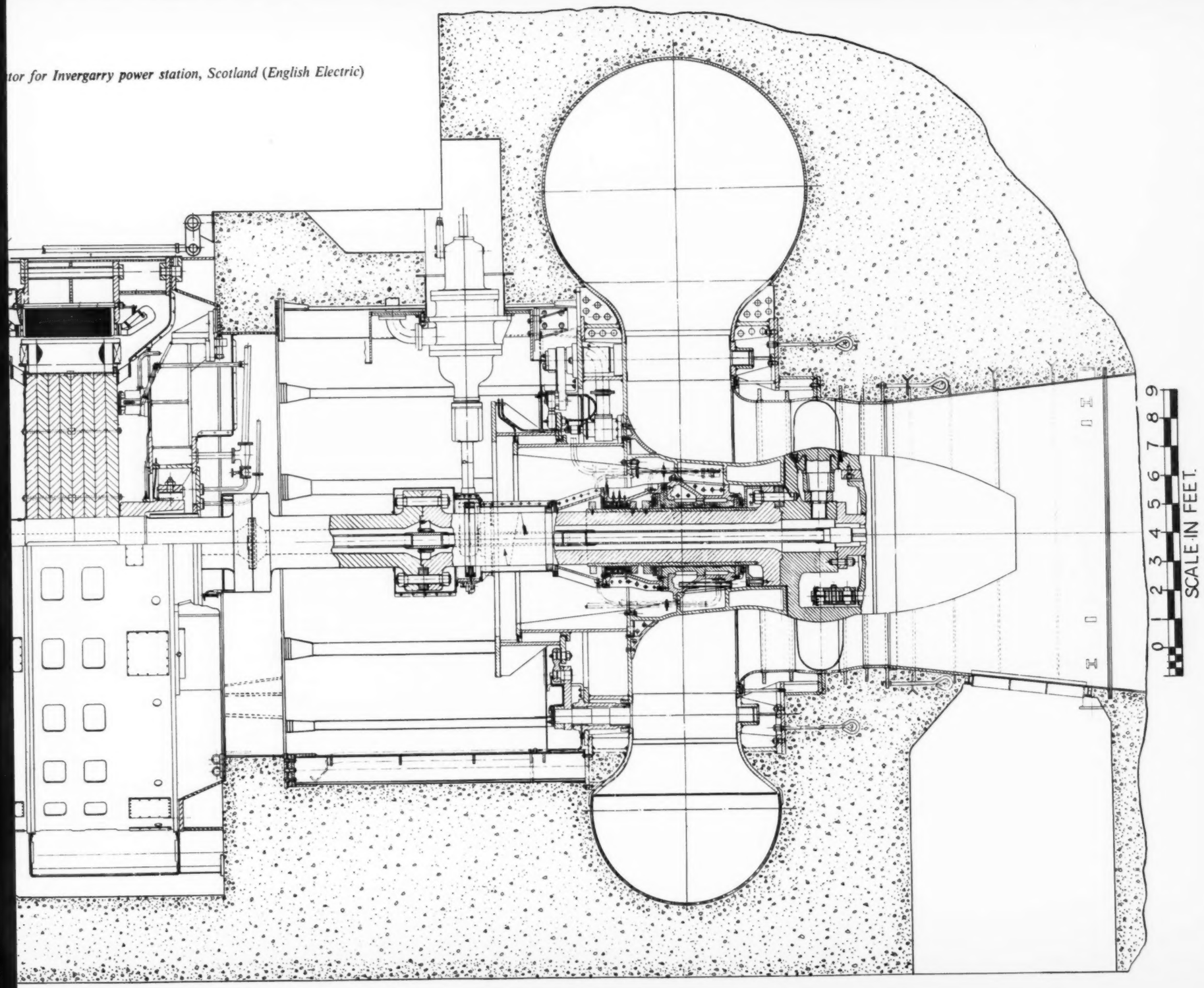
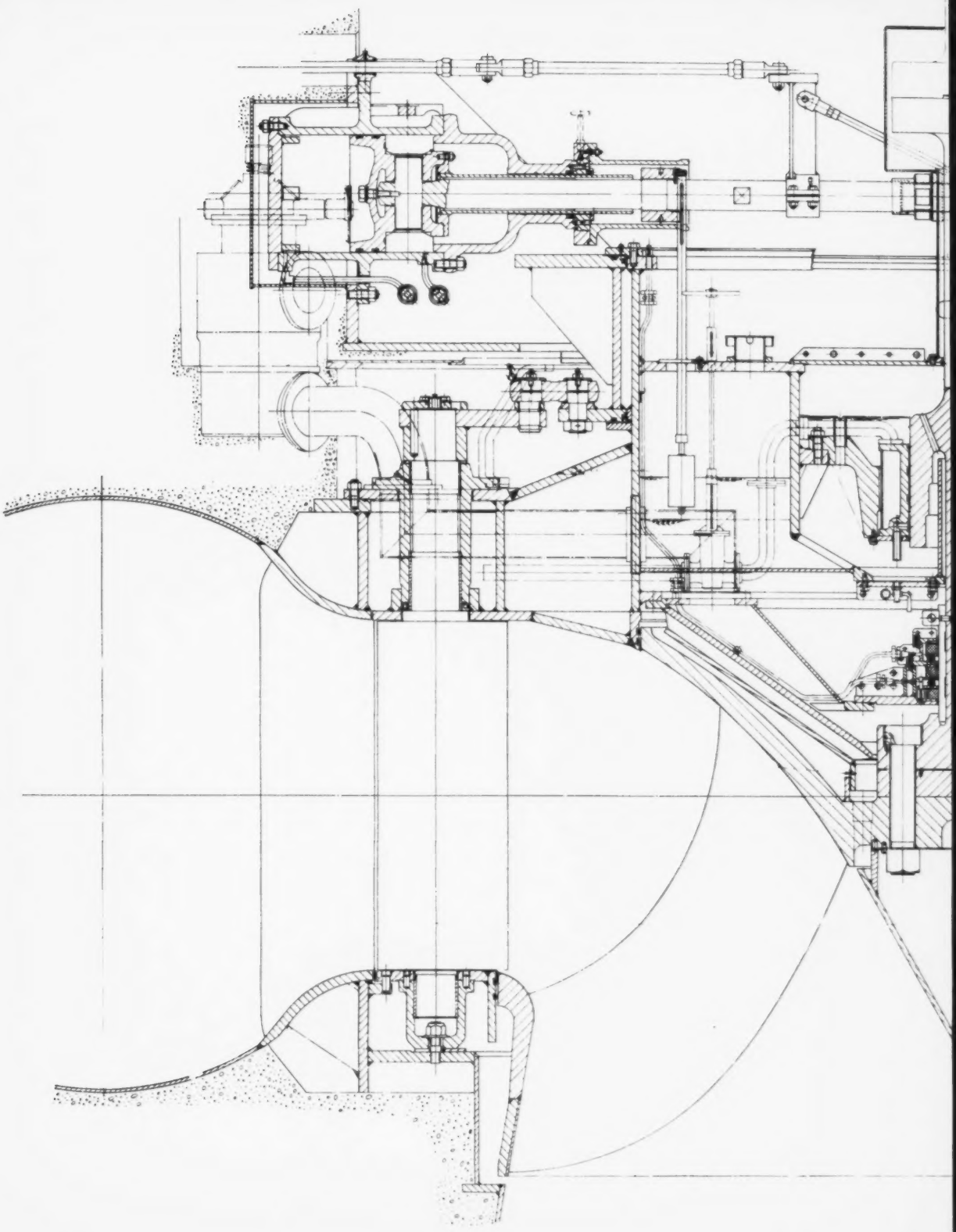




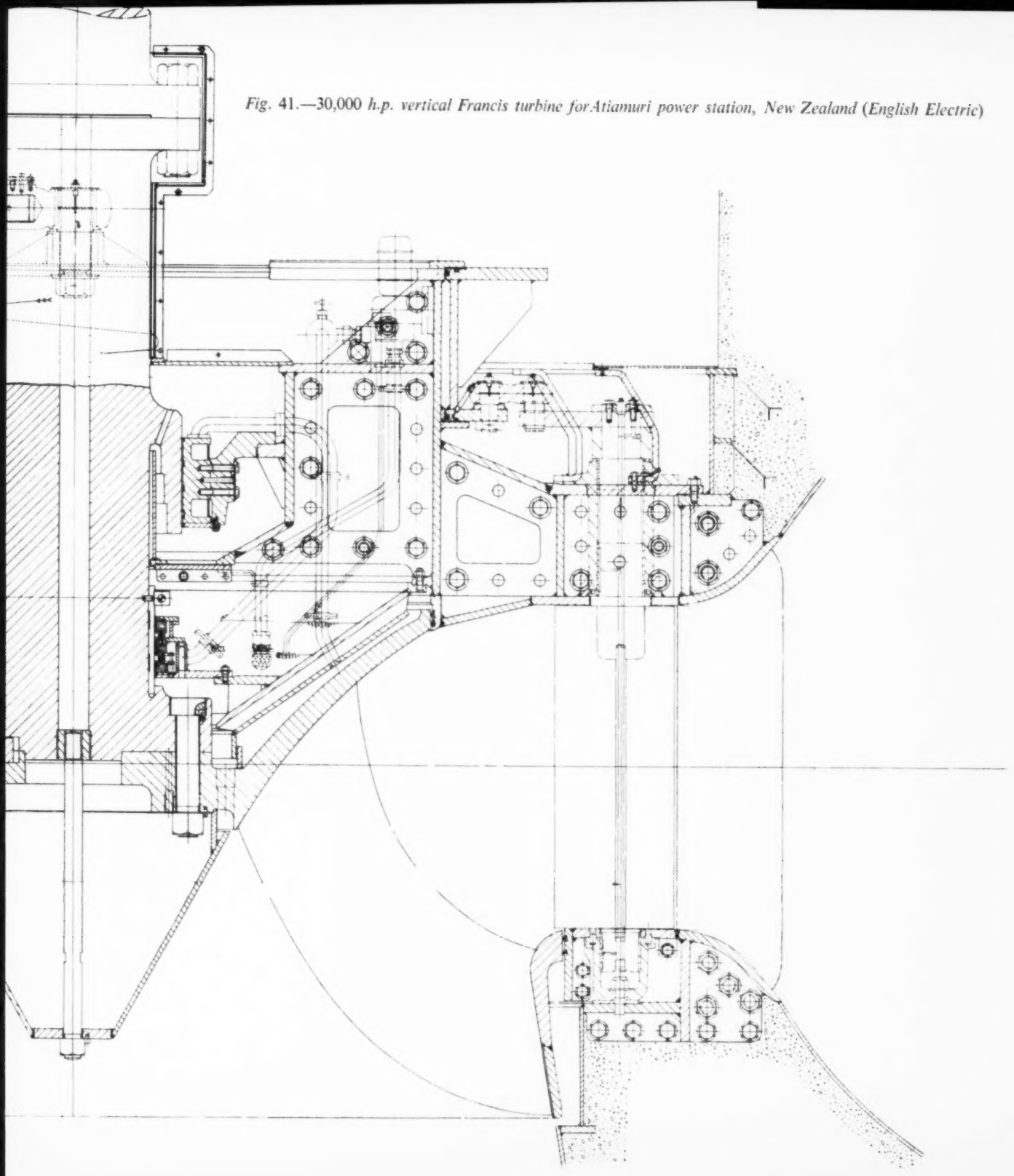


Fig. 41.—30,000 *h.p. vertical Francis turbine for Atiamuri power station, New Zealand* (*English Electric*)

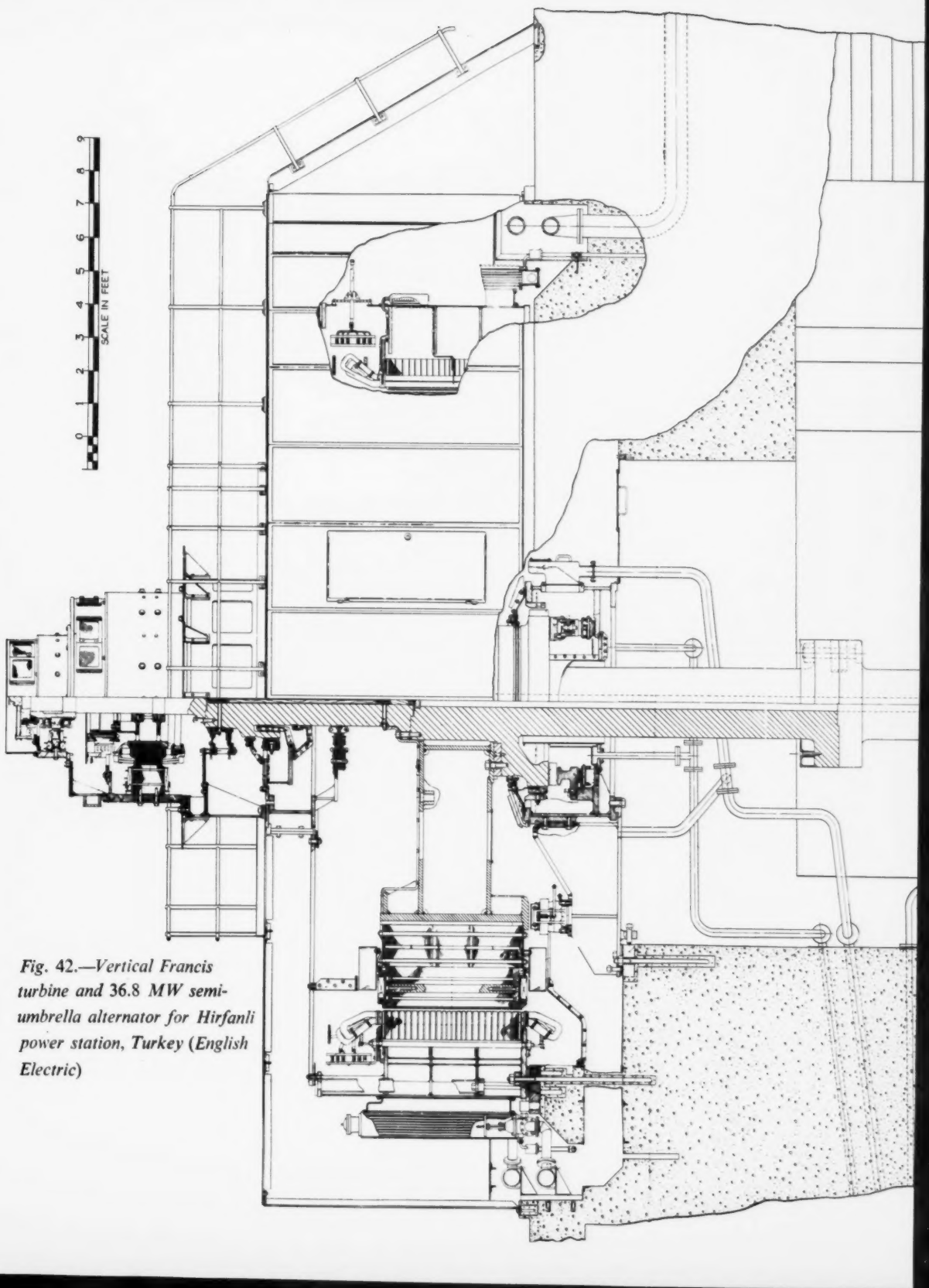
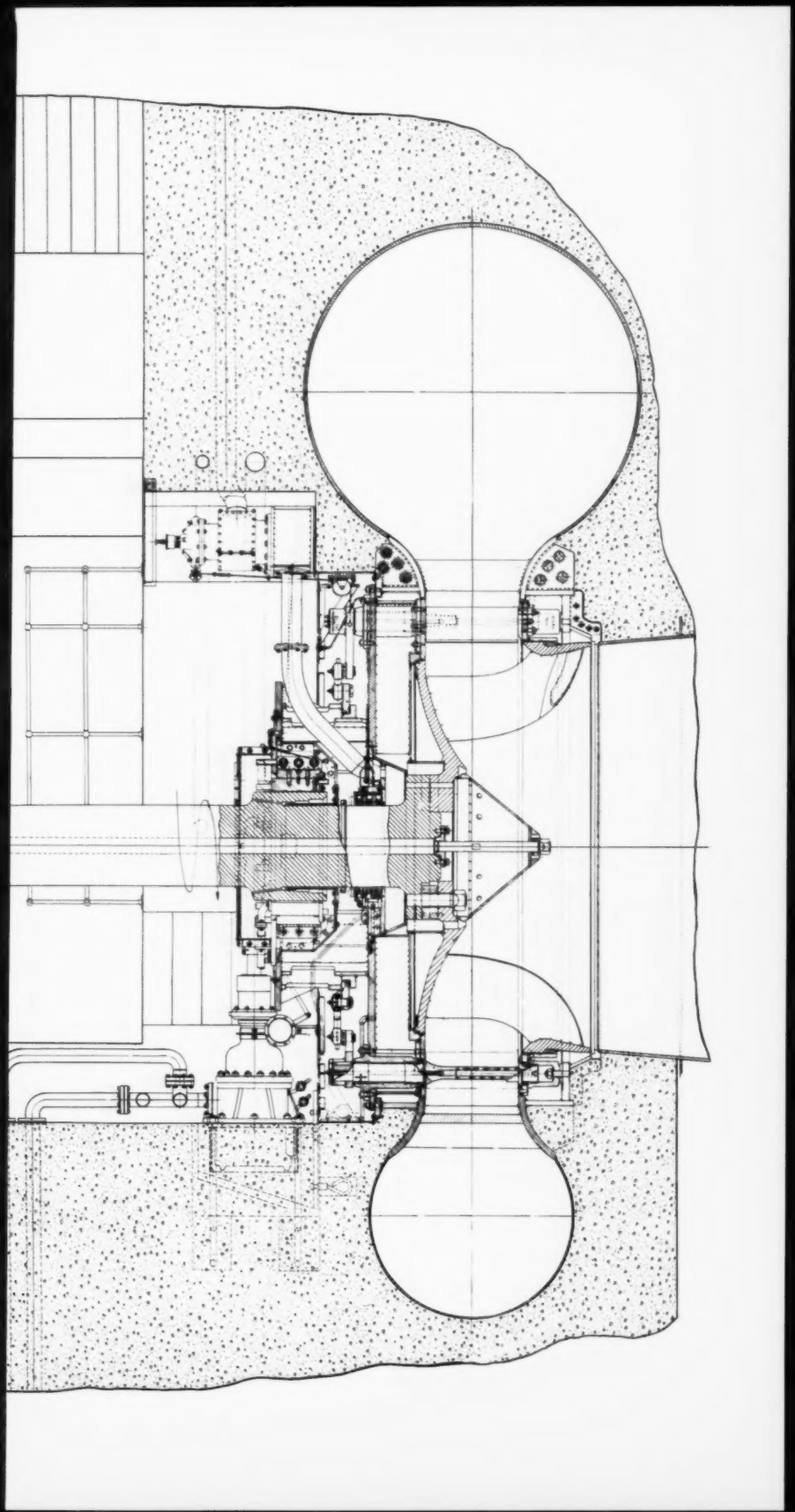
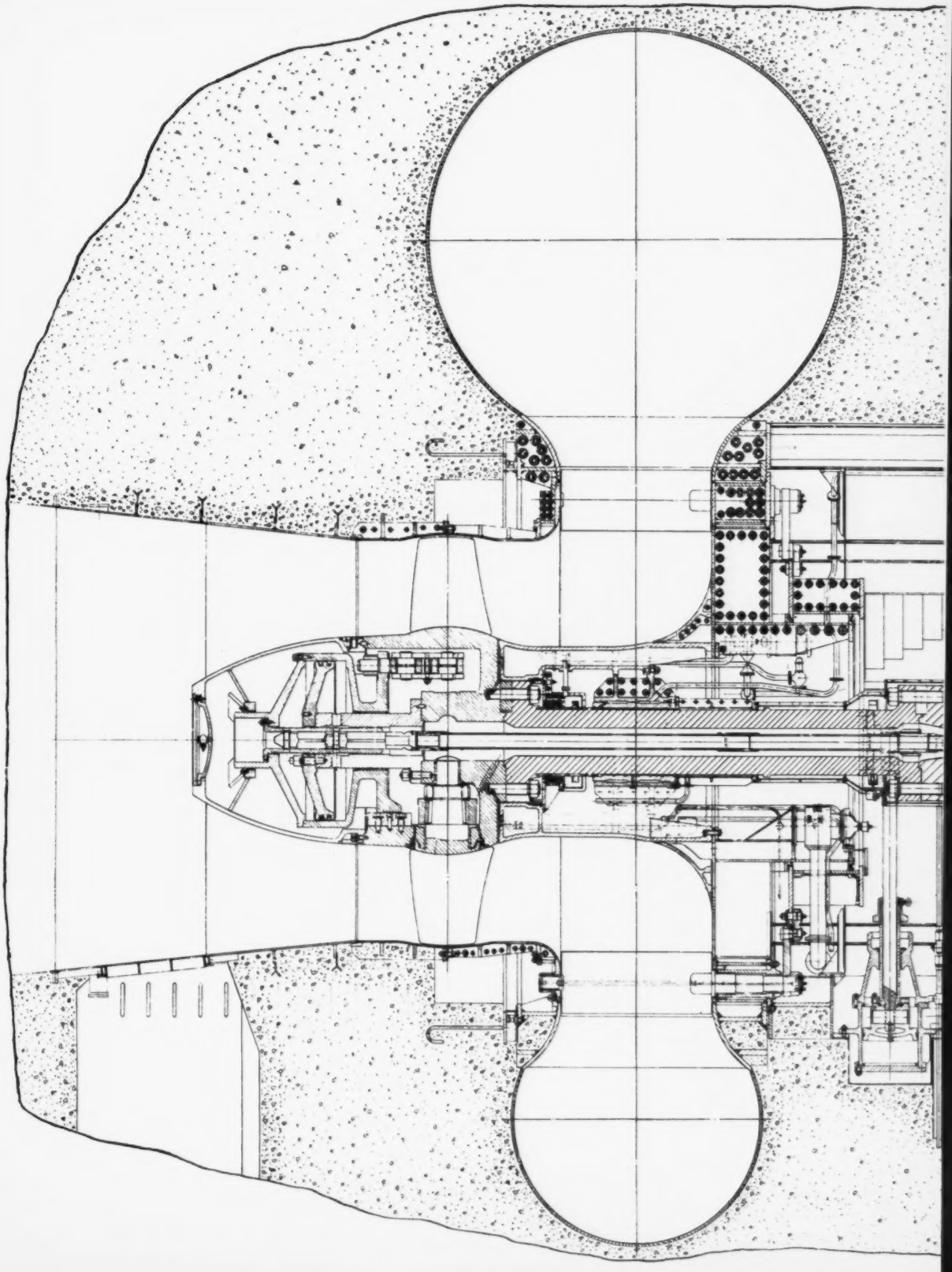


Fig. 42.—Vertical Francis turbine and 36.8 MW semi-umbrella alternator for Hirfanli power station, Turkey (English Electric)





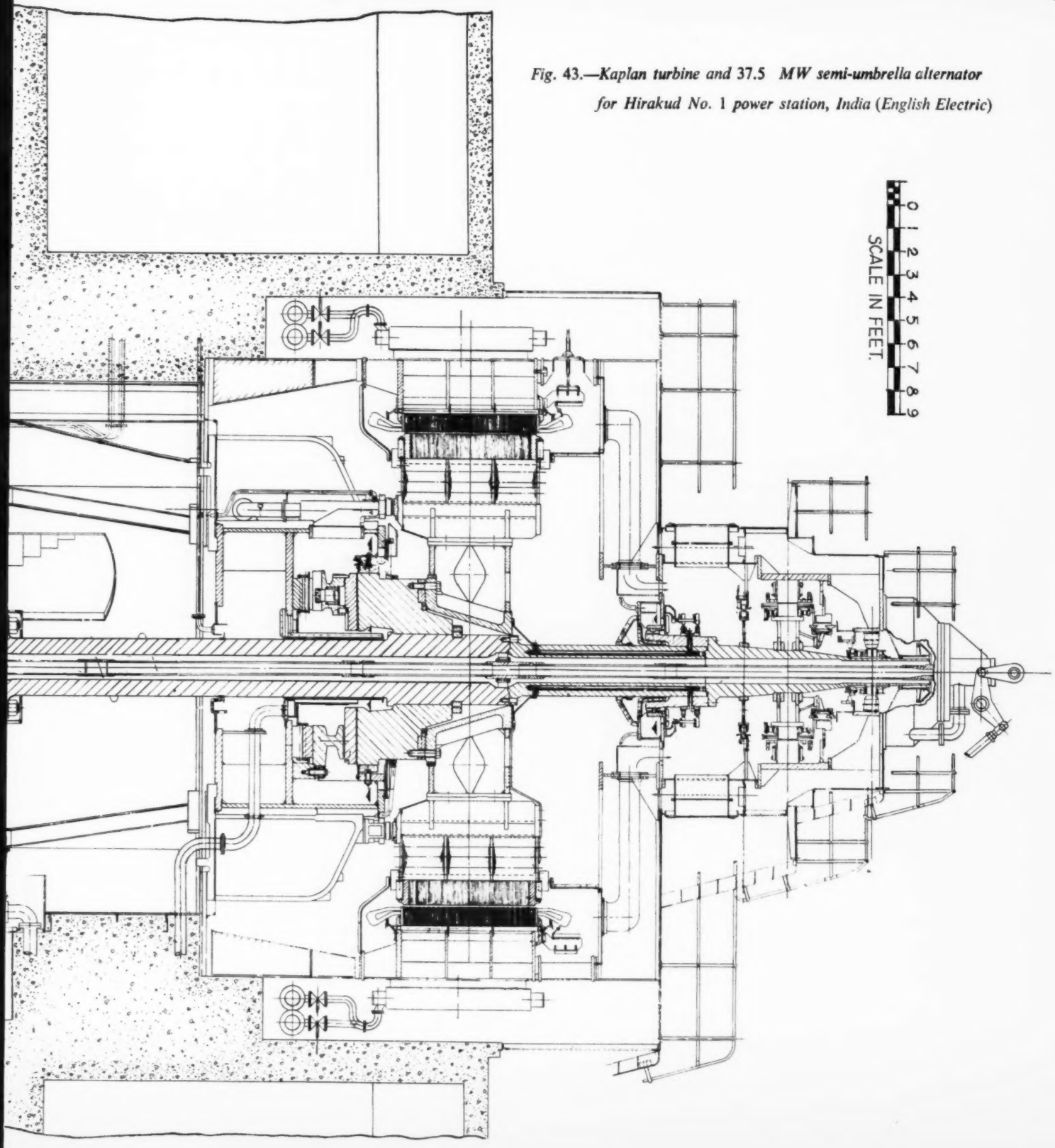


Fig. 43.—Kaplan turbine and 37.5 MW semi-umbrella alternator for Hirakud No. 1 power station, India (English Electric)

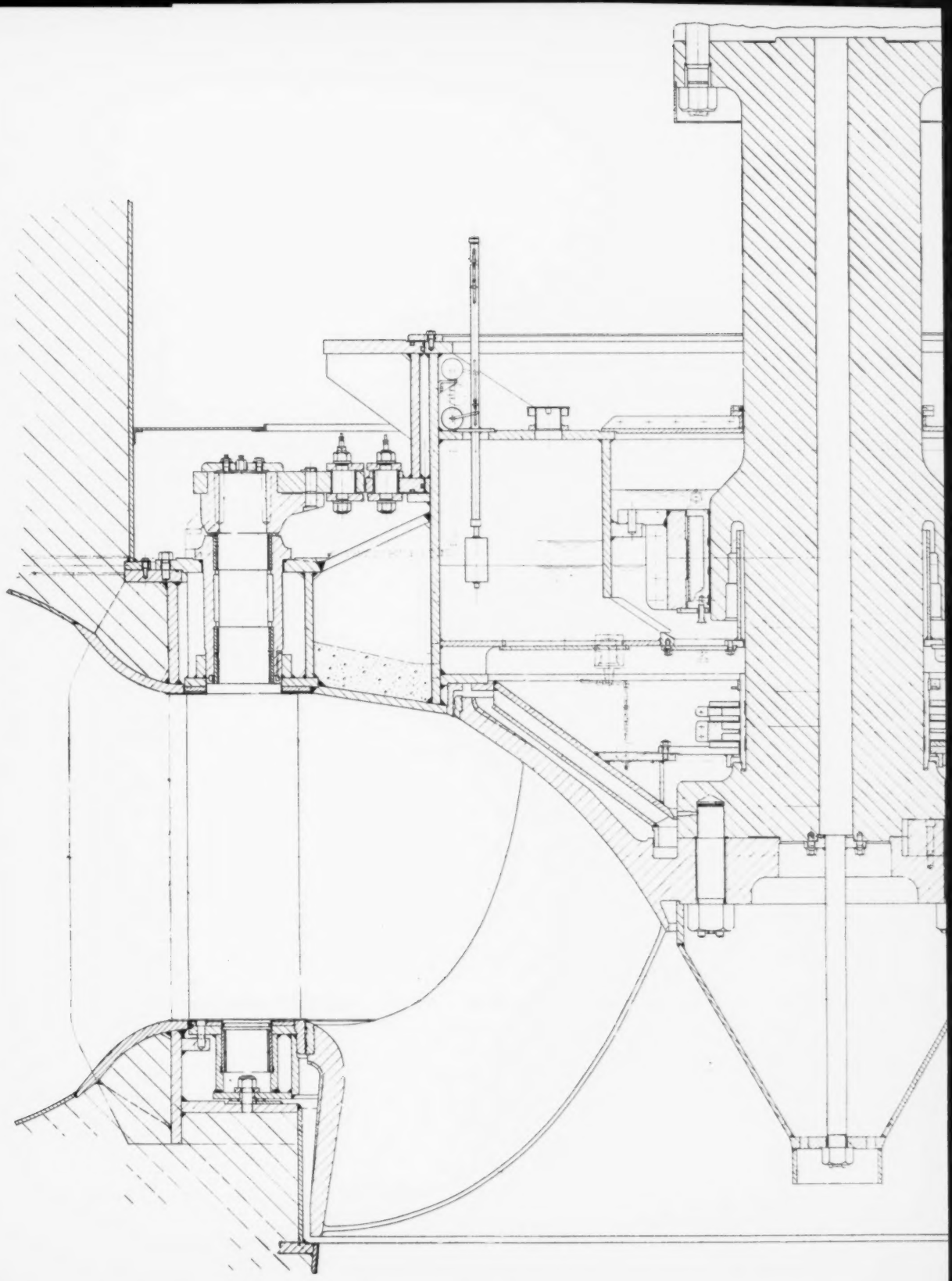
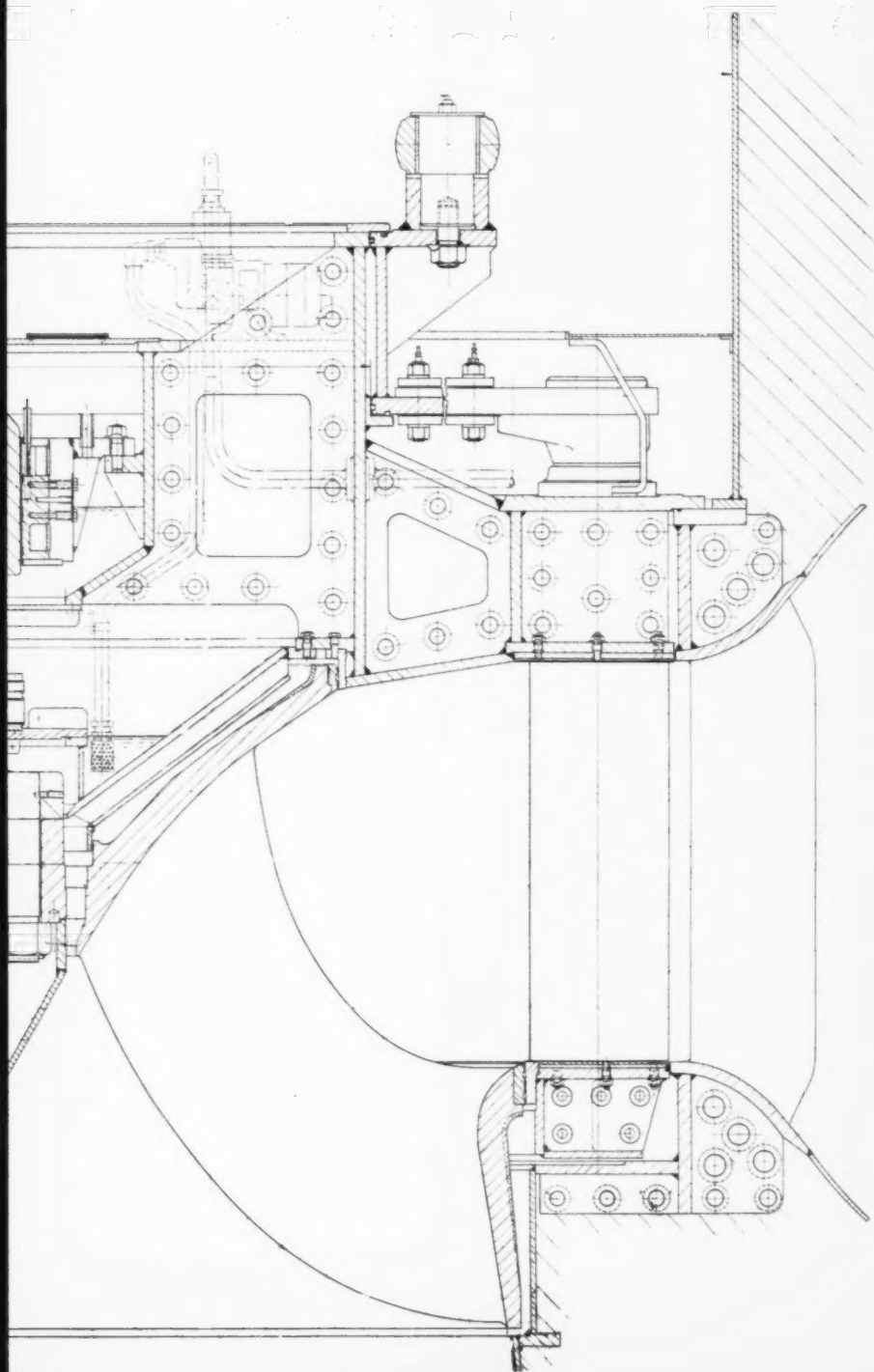


Fig. 44.—62,000 h.p. vertical Francis turbine for Ponte Coberta power station, Brazil (English Electric)



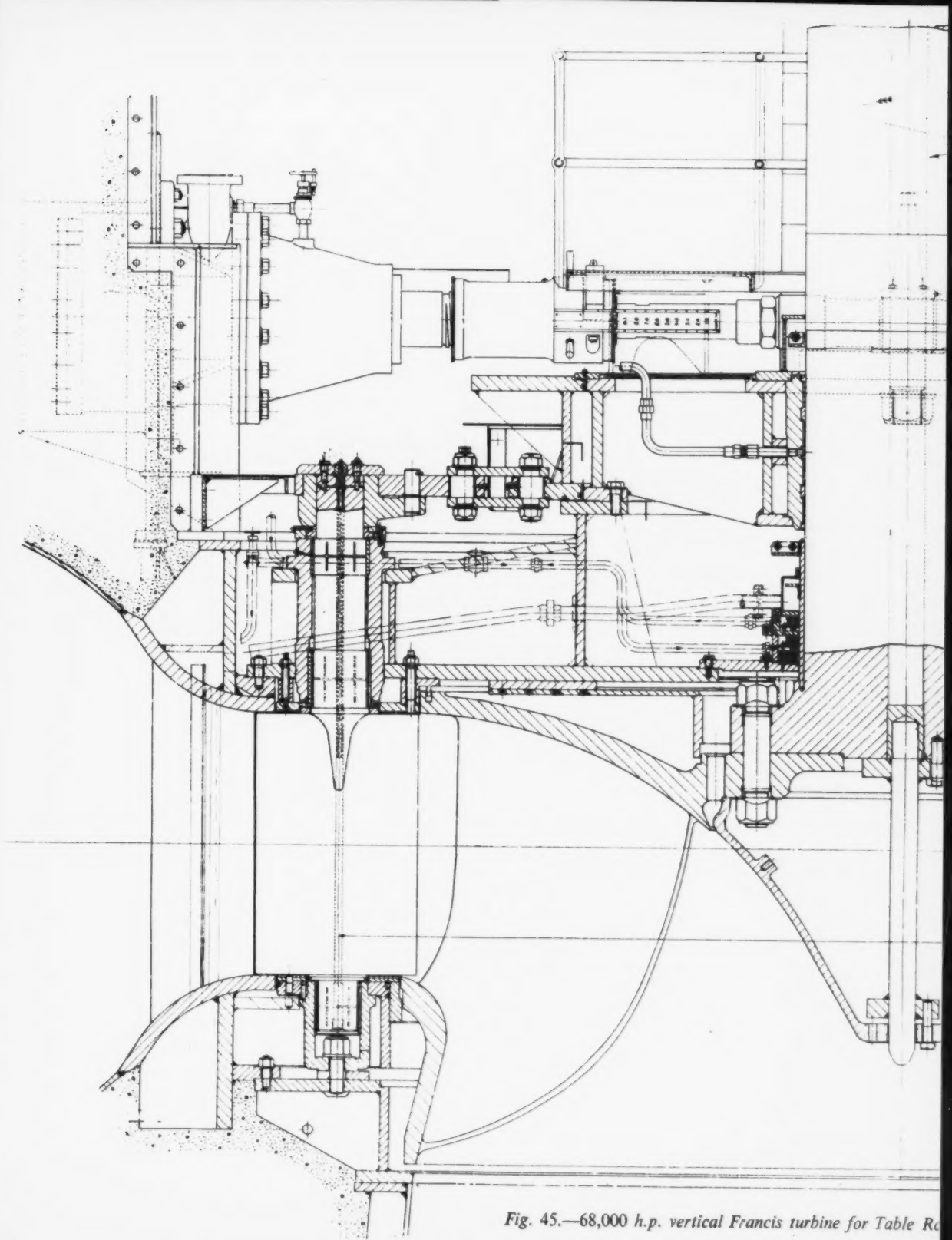
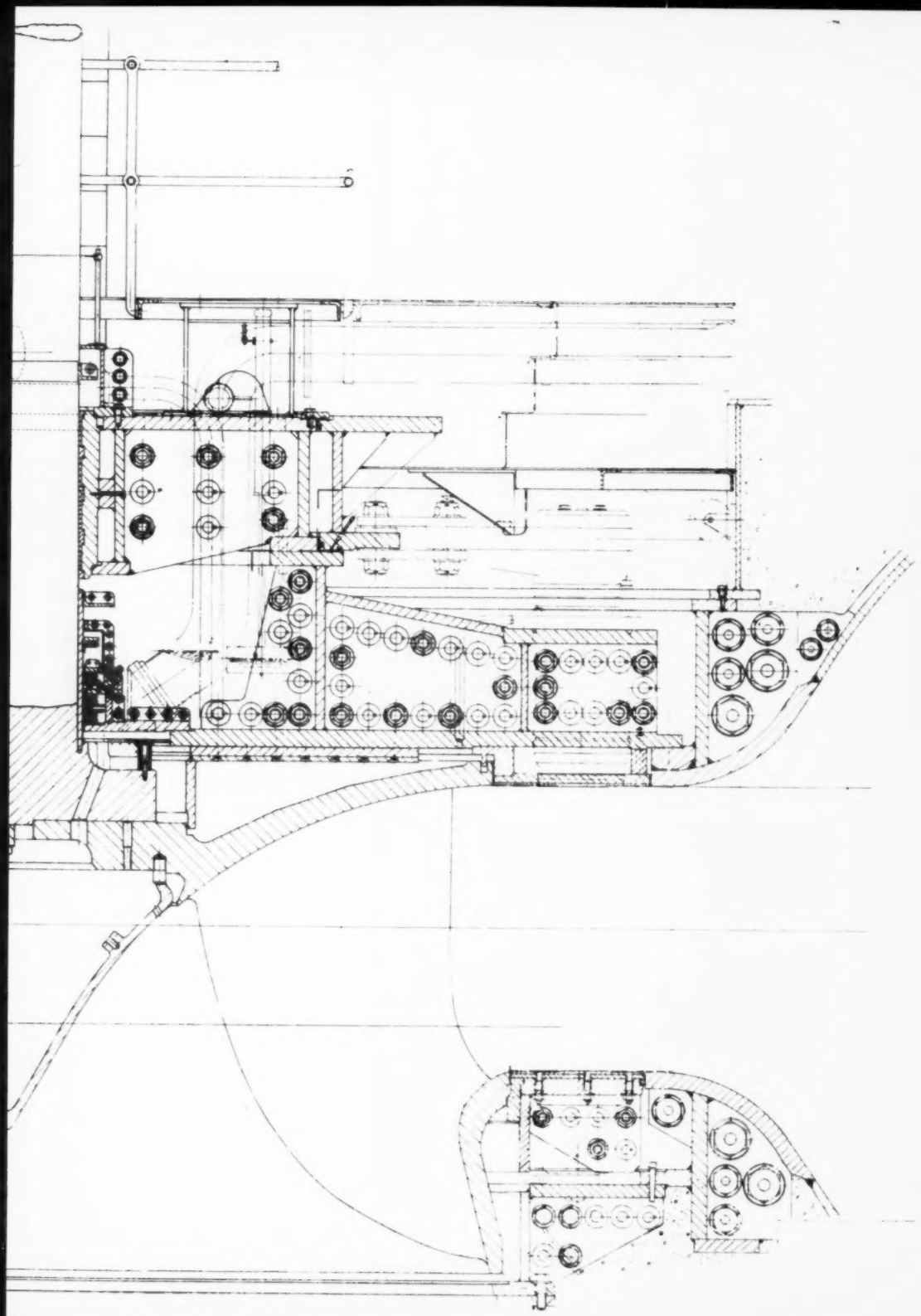


Fig. 45.—68,000 *h.p. vertical Francis turbine for Table R*



ck power station, U.S.A. (English Electric)

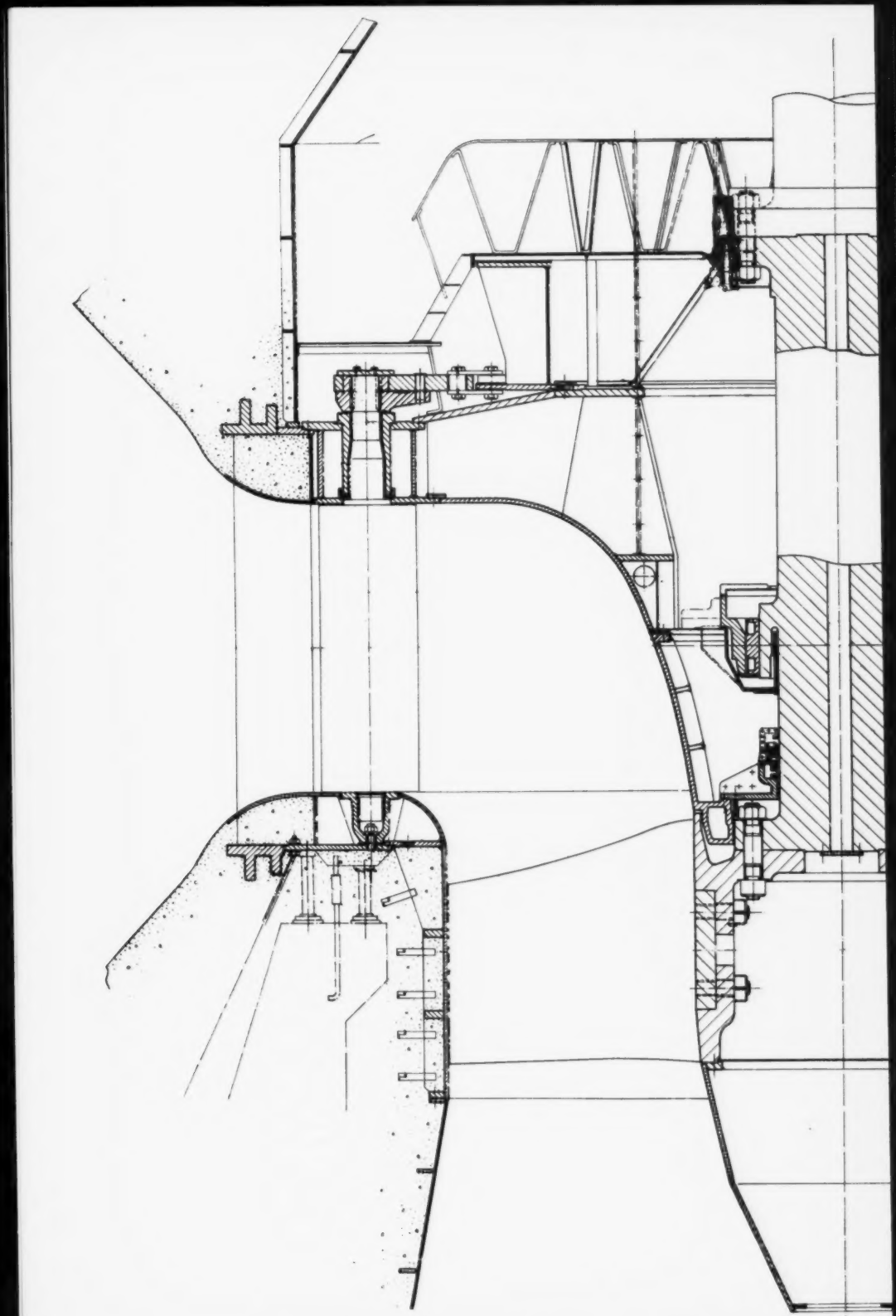
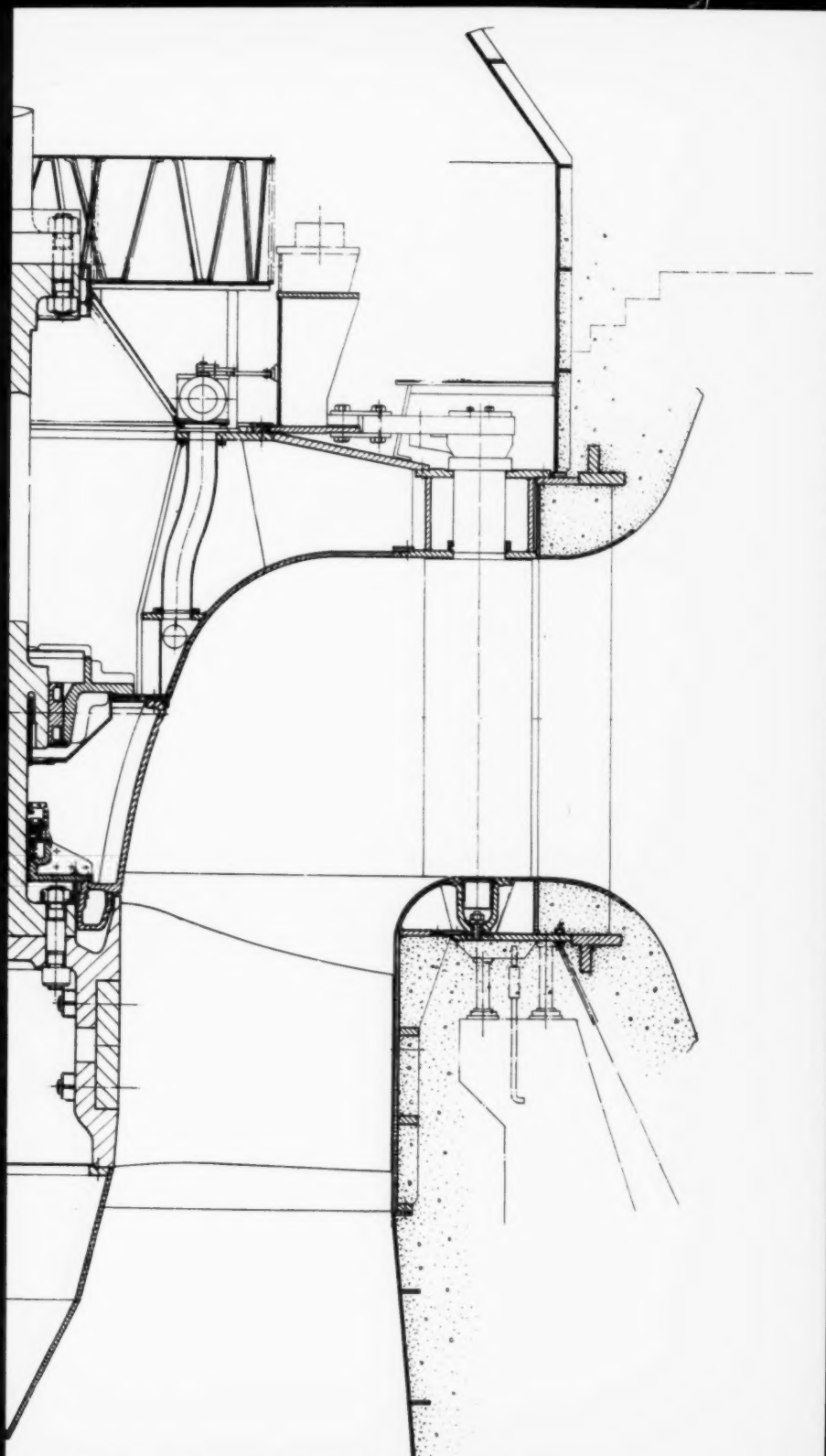


Fig. 46.—75,000 *h.p. vertical propeller turbine for Robert H. Saunders power s*



tation, St. Lawrence Seaway Project, Canada (English Electric)

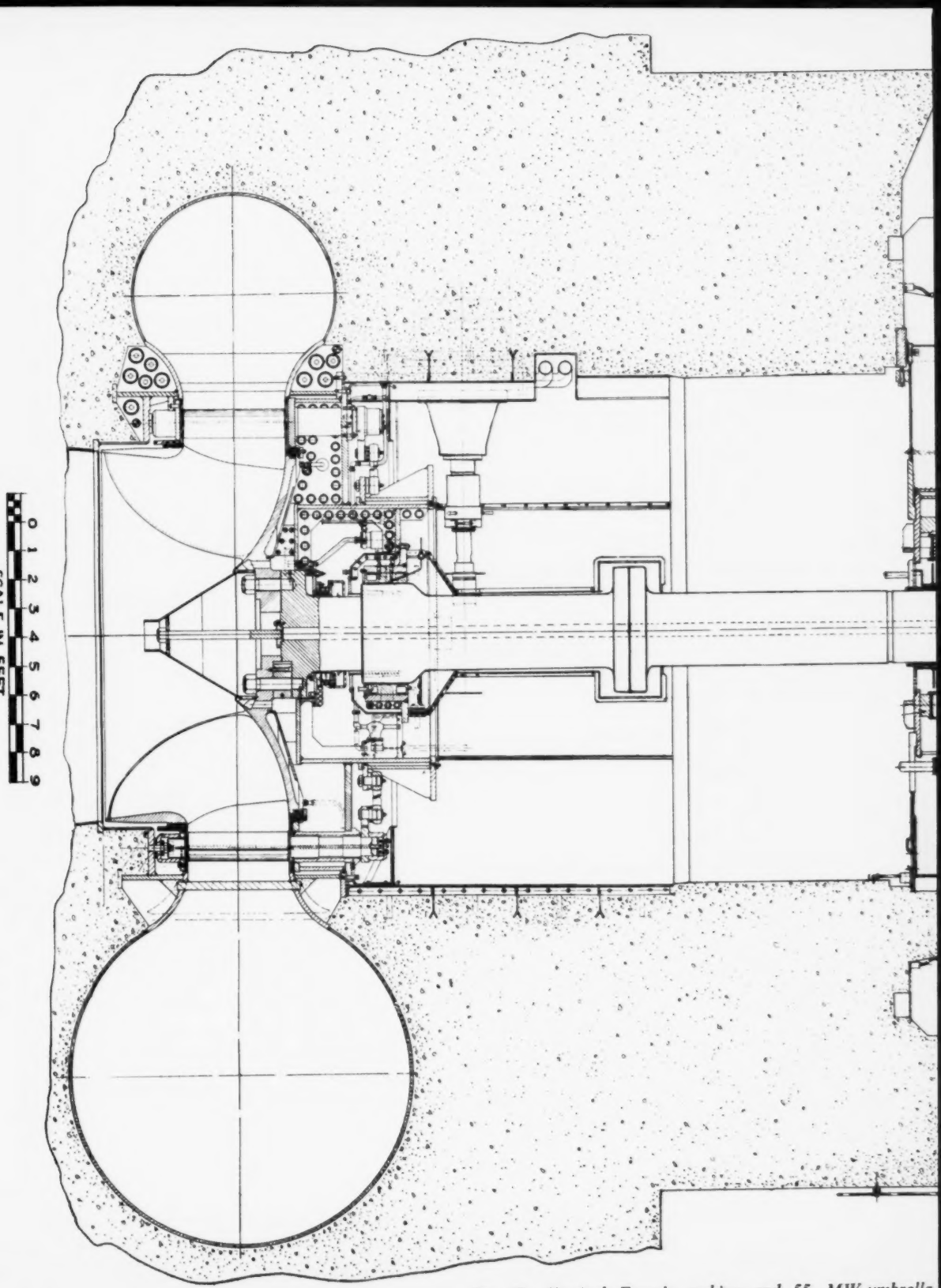
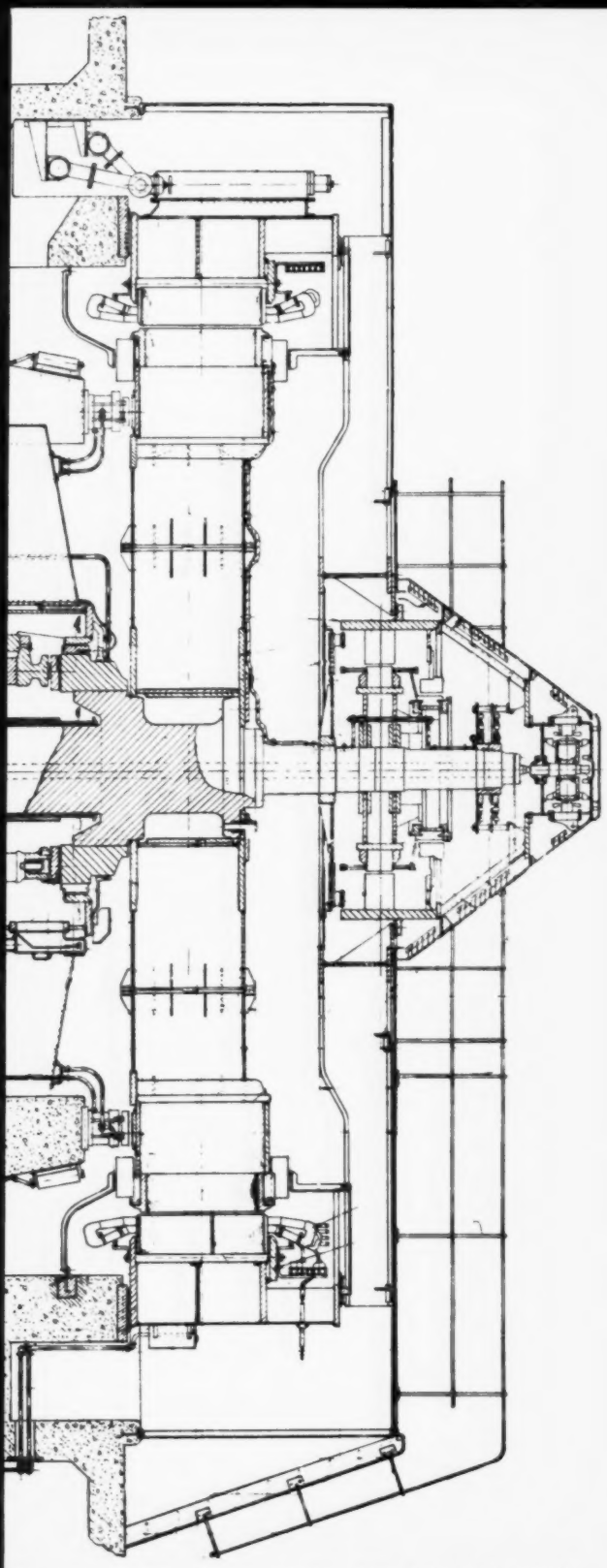
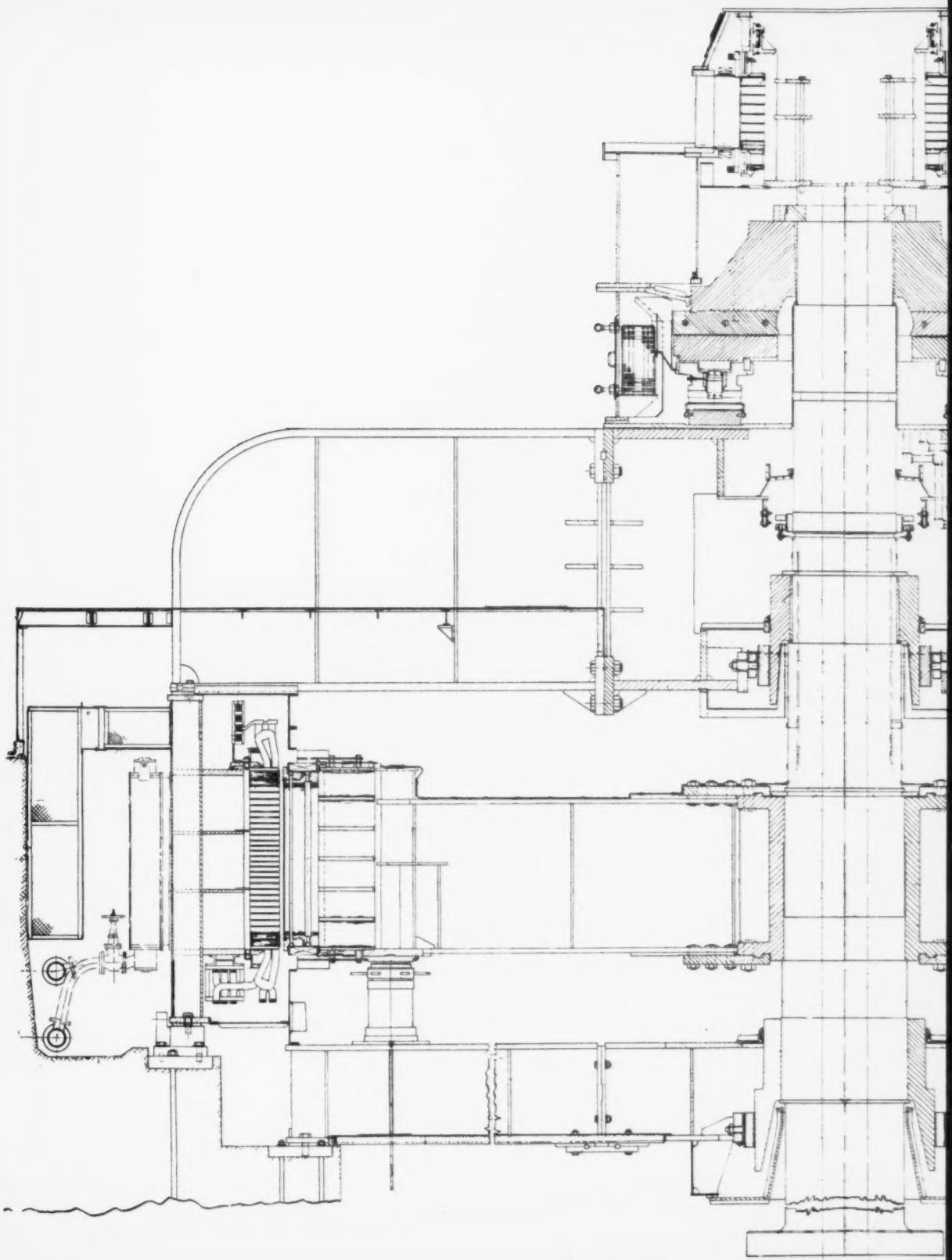


Fig. 47.—Vertical Francis turbine and 55 MW umbrella



alternator for Rihand power station, India (English Electric)



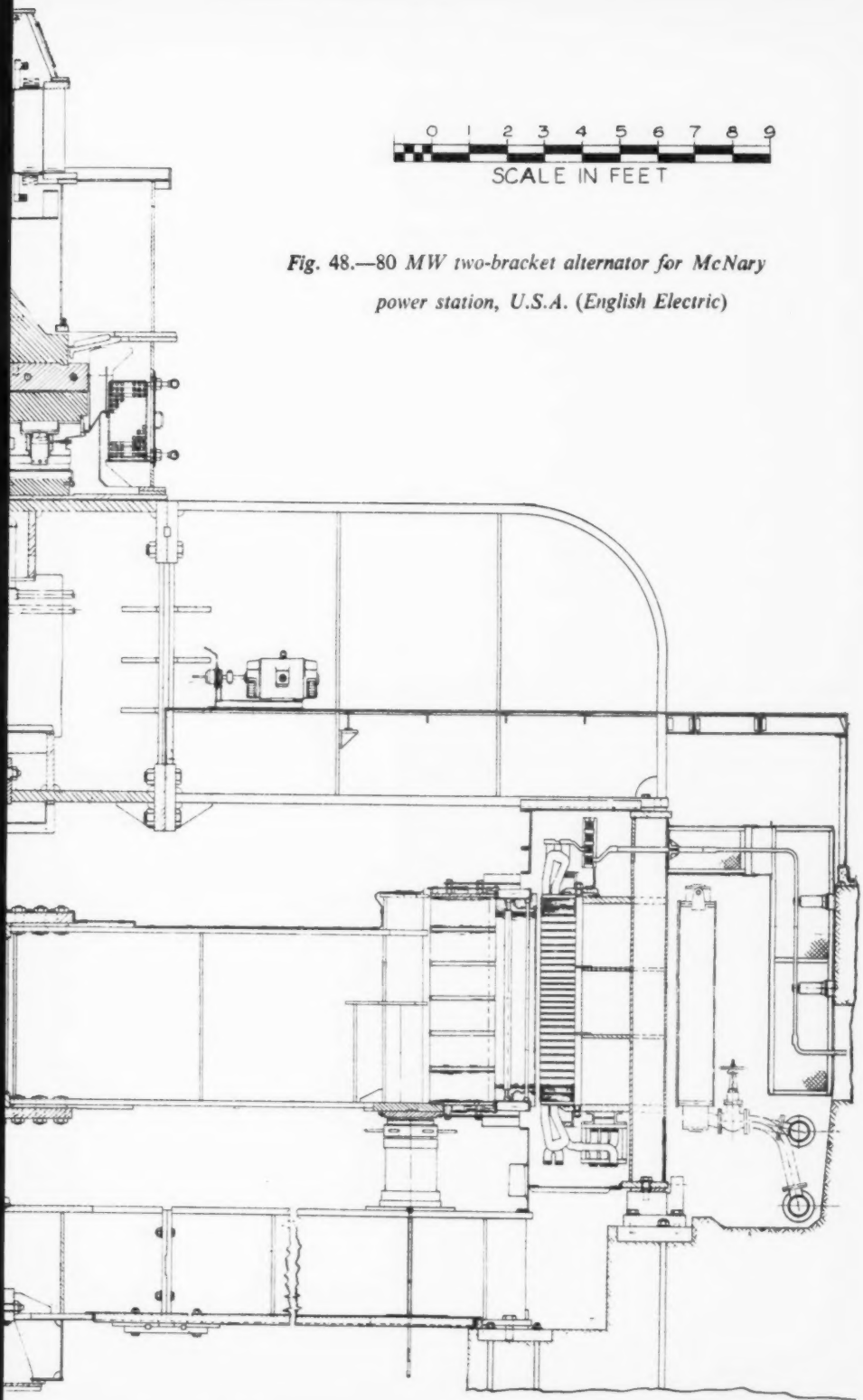


Fig. 48.—80 *MW two-bracket alternator for McNary power station, U.S.A.* (*English Electric*)

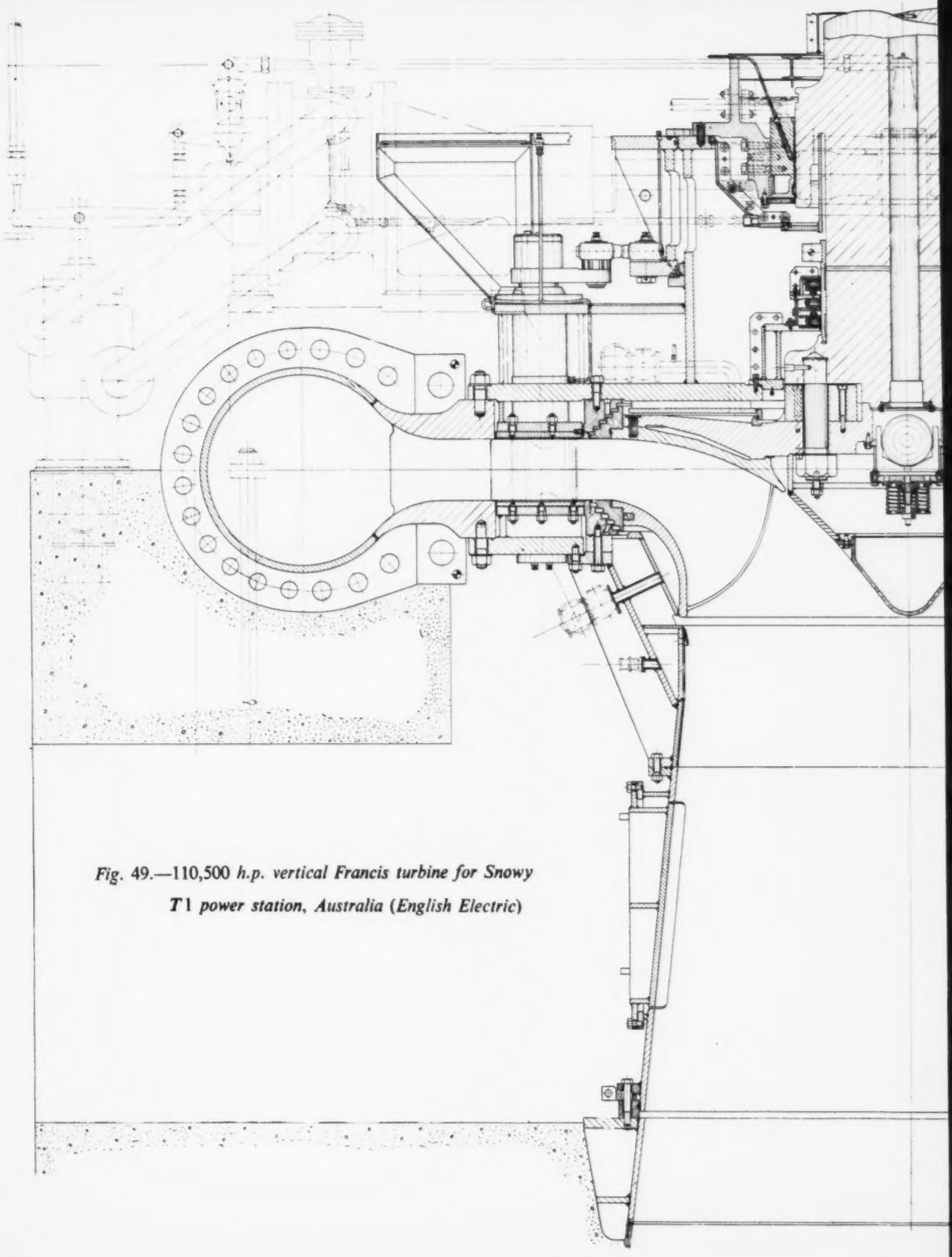
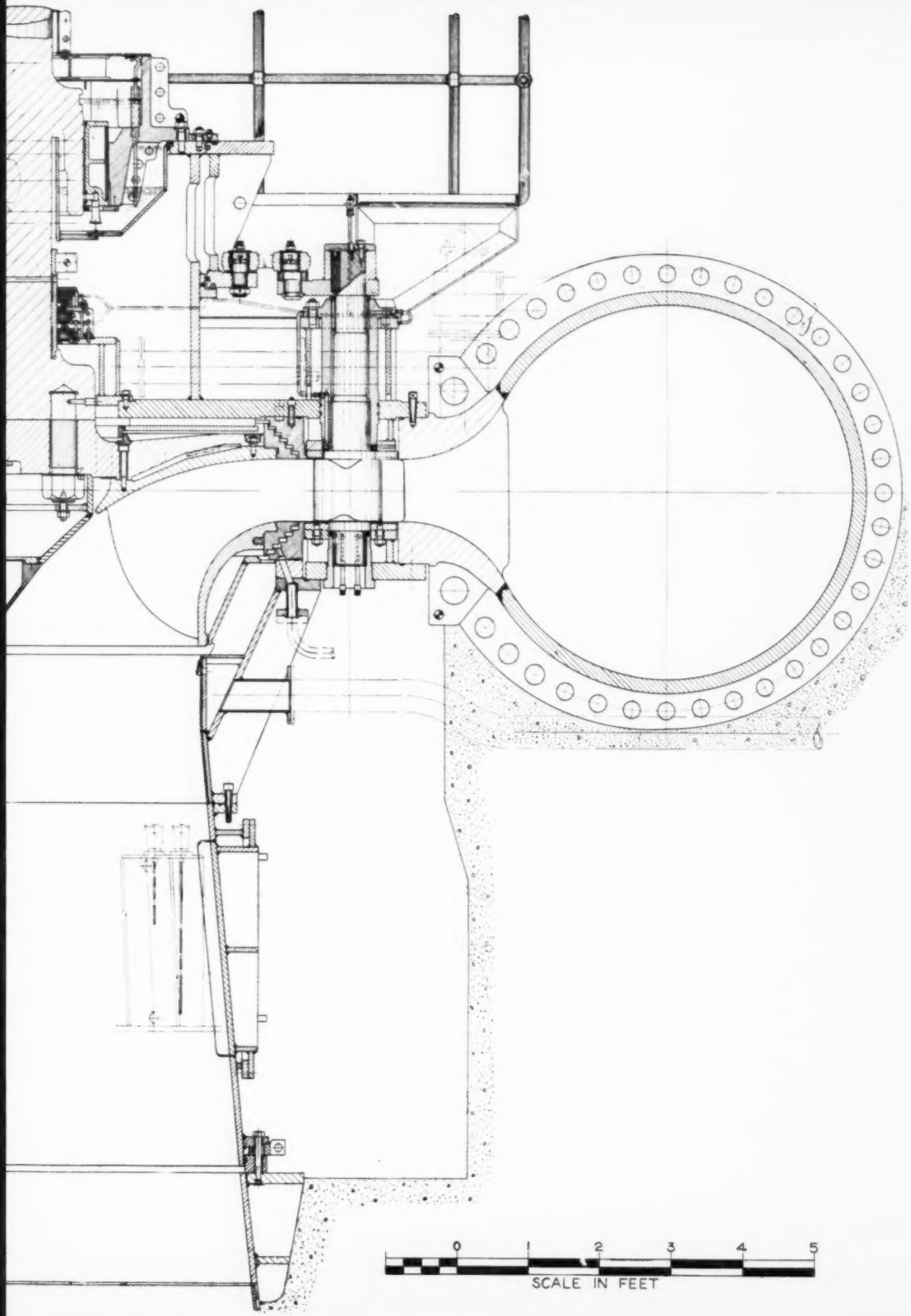


Fig. 49.—110,500 *h.p. vertical Francis turbine for Snowy T*1 *power station, Australia (English Electric)*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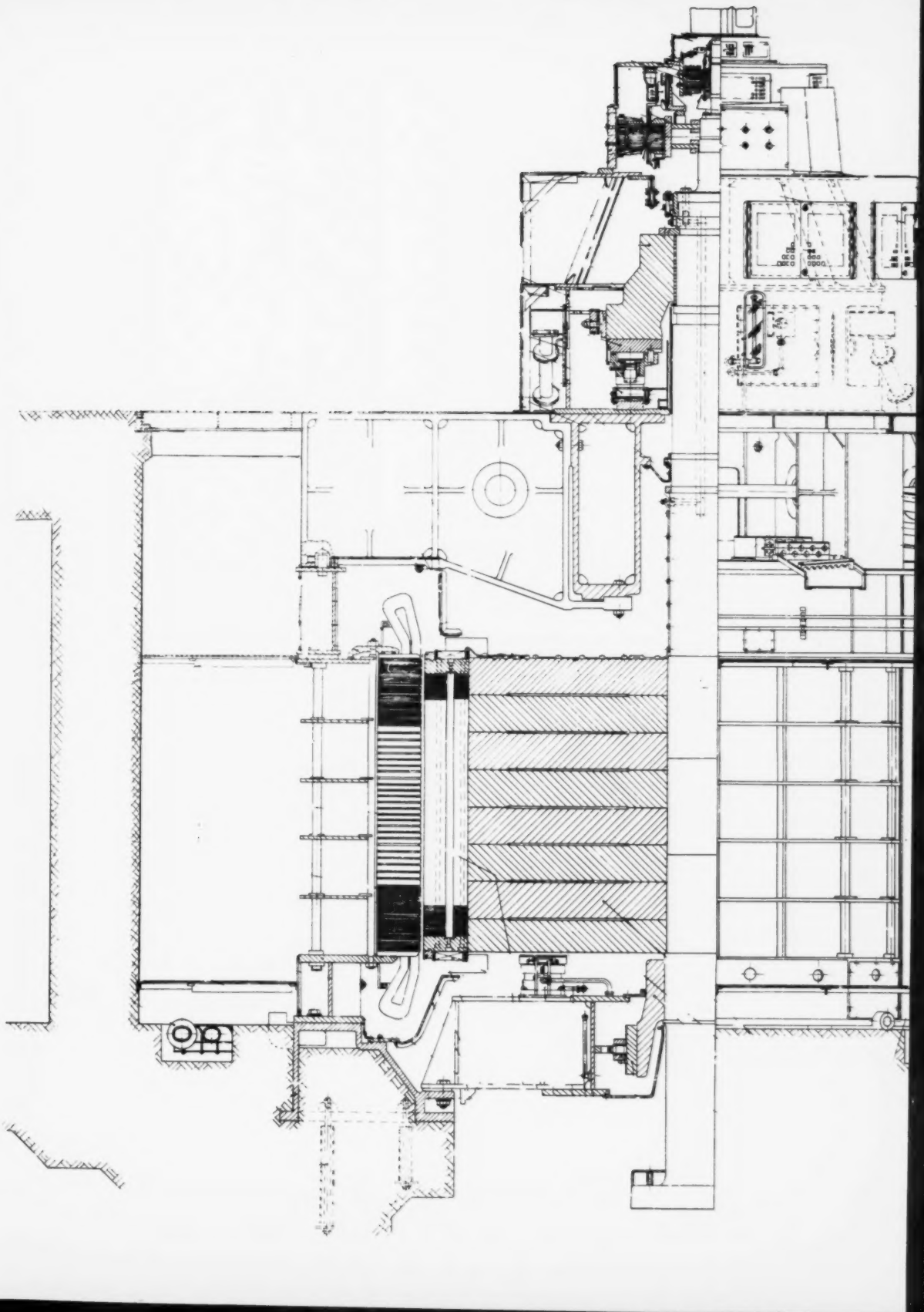
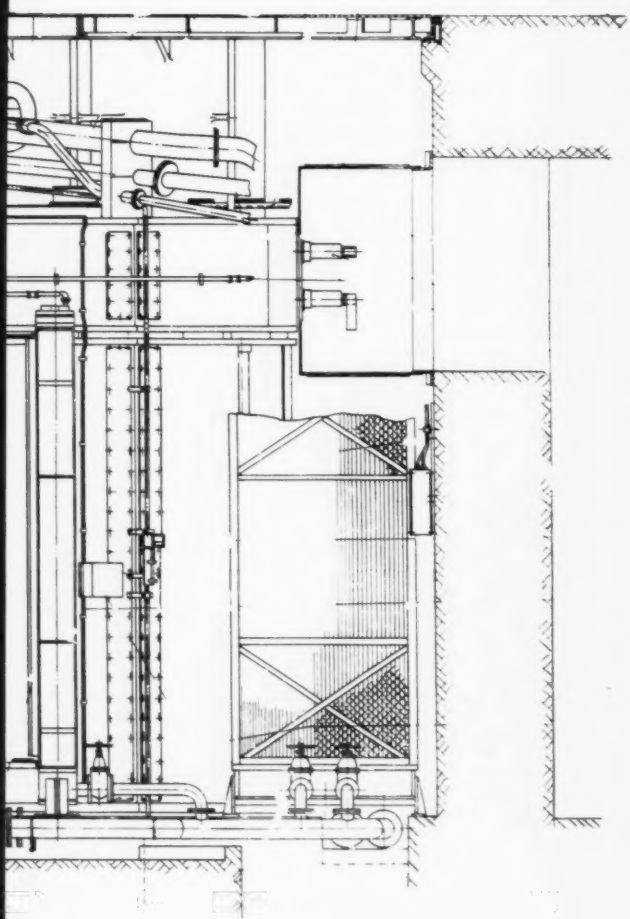
Fig. 50.—106 *MW two-bracket alternator for Kemano power station, Canada (English Electric)*